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REPORT OF THE DECADE:

THE INTERNATIONAL DECADE OF OCEAN EXPLORATION

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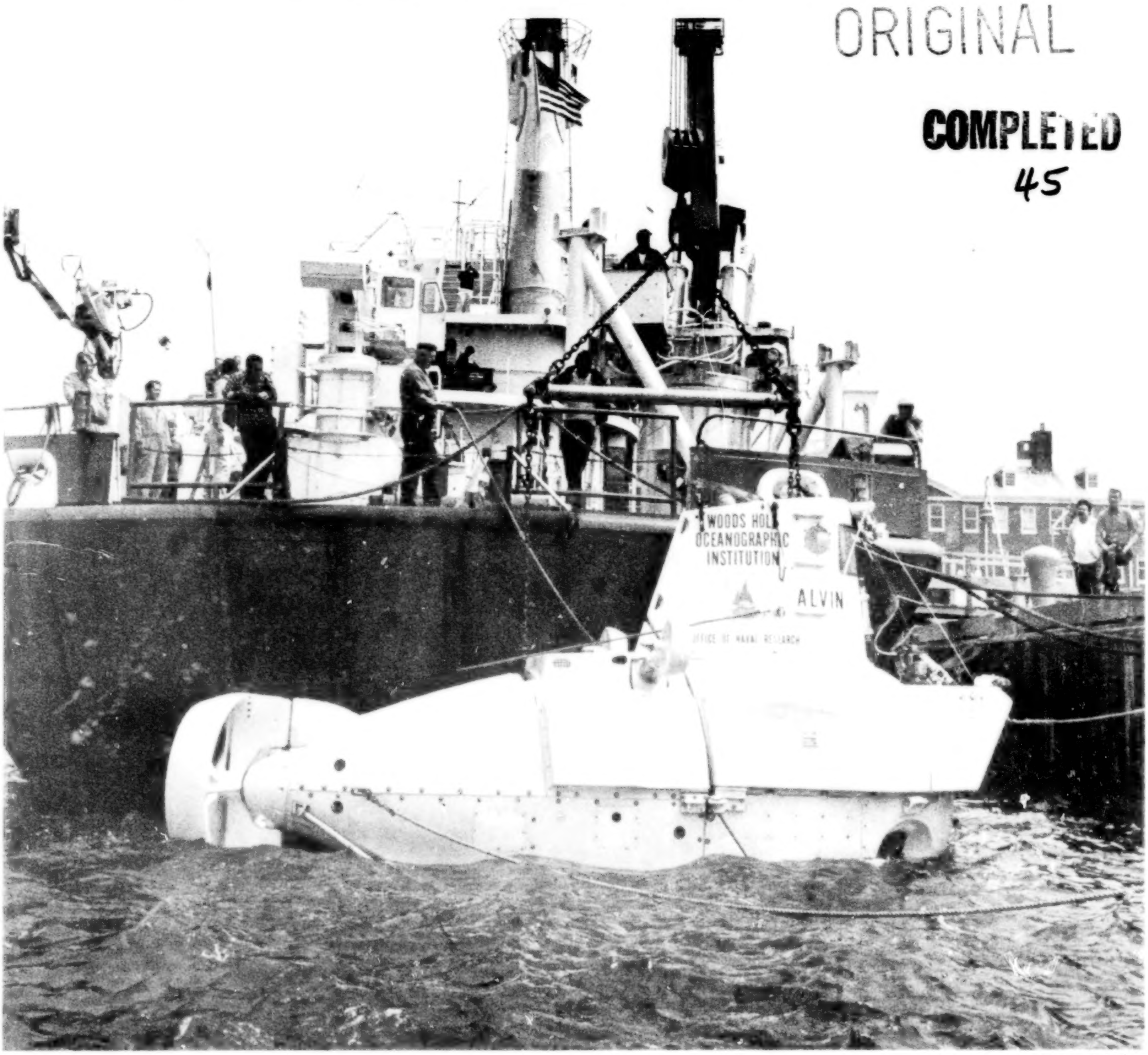

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NATIONAL SCIENCE FOUNDATION
Division of Ocean Sciences
Washington, D.C.

REPORT OF THE DECADE:

THE INTERNATIONAL DECADE OF OCEAN EXPLORATION

28 SEP 1982

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Foreword

The International Decade of Ocean Exploration (IDOE) represented a major investment in time, energy, and public monies to study the ocean and its resource potential. Unlike the spectacular accomplishments in space, the fruits of ocean exploration are subtle. Yet their impact on ocean science, and our view of the earth, is no less profound than that of the moon landings on space science.

This report highlights the history and major findings of the International Decade. It brings IDOE results to those outside the ocean science community and presents the new view of the ocean and its workings that came out of the Decade.

Hundreds of oceanographers from scores of laboratories and institutions and many nations participated in IDOE research. Data analysis from some projects will continue into the early 1980s. Other projects have sparked entirely new investigations that will continue as scientists seek answers to new questions. Research results have been published in scientific journals, memoirs, and atlases. Data from field experiments and research vessel cruises are stored in international libraries; they have been cataloged in IDOE Progress Reports prepared by the Environmental Data Information Service of the National Oceanic and Atmospheric Administration (NOAA).

Just as the IDOE was the joint effort of many individual scientists, this report reflects the cooperation of many persons. Special thanks go to program managers at the National Science Foundation (NSF) and to IDOE scientists who prepared much of the original text. Vicky Cullen, head of the Information Office at the Woods Hole Oceanographic Institution, compiled and edited the text, figures, and captions. Joyce Latham and Bruce Abell, from NSF's Office of Government and Public Programs, helped Lawrence Clark, of the Division of Ocean Sciences, with final editing and preparation.

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Prolog

Study of the ocean has advanced far since its beginnings in 1872, when the converted warship H.M.S. *Challenger*, a full-rigged steam corvette, embarked on a three-year expedition that began the modern exploration of the ocean. A century later, the International Decade of Ocean Exploration (IDOE) marked a major turning point in that exploration and changed the science of oceanography. This section describes the origins of the IDOE, who supported it, and its goals. Following sections will discuss the individual projects within each of the four program areas established for the IDOE by the National Science Foundation.

Beginnings

The International Decade grew out of the many national oceanographic expeditions that were typical of ocean studies before and immediately after World War II. These expeditions were usually made by a single ship covering one or more ocean basins over several years. The resulting picture of the ocean was thus one of averages. Currents were seen as great steady rivers in the sea. The deep ocean was considered rather dark, cold, tranquil, and barren. Thus it was deemed entirely proper to describe ocean circulation and other properties by comparing observations separated by thousands of miles and tens of years. Biologists emphasized the taxonomy or classification of animals in the ocean primarily to work out the evolution of marine species and their biological relationships to one another and to terrestrial groups. In short, the ocean was seen as a rather static part of the planet.

Questions raised during the war showed the need for a better understanding of the ocean. Accurate navigation and the ability to detect submarines required far better knowledge of how sound travels in the sea. Amphibious landings demanded better wave forecasts and clearer definition of the relationships between ocean and atmosphere. Battles for the coral islands of the South Pacific showed our ignorance of these land masses and how they grew.

As a result of these needs, support for ocean research continued after the war, coming mostly from government agencies, especially the U.S. Department of Defense. Oceanography departments arose at many universities to train students, and continued government support led to research and ship facilities far beyond those available before the war.

These new resources also enabled multi-ship investigations of the ocean's dynamic features. The Gulf Stream studies in the 1950s showed that the "great river in the sea" actually meandered significantly and had reverse flows at certain depths. Although earlier studies had suggested these movements, confirmation was possible only by using more extensive facilities than those previously available to a single institution.

New instruments also played a major role in the postwar period. The Swallow float, designed by British oceanographer John Swallow, floated at a predetermined depth and emitted acoustic signals that could be tracked by a ship on the ocean surface. With this instrument, deep-ocean currents could be directly plotted for the first time, and they proved to be far more dynamic than predicted. The classical model of ocean circulation had currents moving sluggishly as thin sheets from their sources in the high latitudes and eventually mixing with surrounding waters until they lost their identity. Swallow's observations near Bermuda in the late 1950s showed that floats at different depths moved quite rapidly in several different directions, many of them following spiral paths rather than the expected uniform track.

Systematic studies of the ocean showed that careful surveys made in a short time period could identify features such as currents, discrete water masses, and other properties and could determine their importance with a precision not possible using averaged and randomly spaced observations. Later questions about the ocean's health and possible worldwide contamination of its surface argued for a baseline survey—a global examination of ocean conditions that would be a benchmark for future studies.

The International Decade of Ocean Exploration was a response by many nations to the increased awareness of the ocean's importance. In the 1960s, optimistic scientists forecast that millions might be fed with increased catches of fish from the sea. They told of billions of tons of scarce copper, nickel, and cobalt to be recovered from manganese nodules on the deep-ocean floor. In sharp contrast, other scientists depicted an ocean dying because of oil dumped from tankers on the high seas. And people were dying in Japan, apparently from eating shellfish poisoned by mercury that factories discharged into coastal waters. Another factor was the threat to the long-established legal regime of the open ocean. This threat arose from the developing nations' desire for a share in this new source of wealth.

From these diverse origins came the IDOE. Dr. Edward Wenk, of the University of Washington, described the Decade idea in his book, ***The Politics of the Ocean***. The IDOE looked to a systematic program of ocean exploration motivated by anticipated uses of marine resources as much as by scientific curiosity. The new idea was not just a continuation or even a simple expansion of past research efforts. Instead, exploration of the seas was to be a sustained effort, a global venture rather than a patchwork of national programs or a loose collection of projects by individual scientists. It would bring together users as well as producers of scientific knowledge. It would help nations with modest ocean research capabilities to expand their programs. And IDOE projects would foster good will by exchanges between governments and collaboration between scientists.

Some original Decade goals were not pursued when it became clear that the funding levels originally anticipated would not be reached. Management of IDOE programs was hampered by less-than-ideal coordination among participating federal agencies and by an academic community unaccustomed to working on tightly coordinated projects. Thus some early goals were not met, including an ocean-monitoring system and the uniform application of research results to improve management of marine exploration. But most scientific goals were met and far exceeded.

For ocean-going scientists, IDOE meant an opportunity to use ships, new instruments, and the emerging technologies of computers and satellites to answer some of the most important and challenging questions in ocean science:

- The ocean's role in controlling climate.
- Interactions between ocean and atmosphere.
- Unknown processes of the sea floor.
- Physical and chemical interactions controlling the way pollutants are spread in the ocean.
- Links between ocean circulation and the rich productivity of the world's most important fisheries.

All these unknowns had been recognized in the 1960s. However, a concerted attack on them was beyond the resources of individual investigators or even nations. The IGY or International Geophysical Year (1957-58) had shown glimpses of the returns promised by large cooperative endeavors; IDOE provided funds and organization to attack these problems. The result: exciting discoveries of the 1970s have changed our view of the ocean and the way oceanographers will work there in the 1980s and beyond.

Launching the Decade

In 1966 the United Nations General Assembly asked the Secretary General to survey the marine science and technology work of U.N. member states and of intergovernmental and private international groups. He was then to suggest how best to come up with a wider program of international cooperation in this field. It was obvious then, as now, that nearly all ocean issues transcended national boundaries. U.S. President Lyndon B. Johnson reflected this awareness when he commissioned the research vessel ***Oceanographer*** in July 1966. He observed that:

> Truly great accomplishments in oceanography will require the cooperation of all the maritime nations of the world. And so...I send our voice out...calling for such cooperation, requesting it, and urging it.... We greatly welcome...international participation. Because under no circumstances, we believe, must we ever allow the prospects of rich harvests and mineral wealth to create a new form of colonial competition among the maritime nations. We must be careful to avoid a race to grab and to hold the lands under the high seas. We must ensure that the deep seas and the ocean bottoms are, and remain, the legacy of all human beings.

In March 1968, President Johnson endorsed the idea of an International Decade of Ocean Exploration. In a special conservation message to the Congress entitled "To Renew a Nation," he said:

> The task of exploring the ocean's depth for its potential wealth—food, minerals, resources—is as vast as the seas themselves. No one nation can undertake that task alone. As we have learned from prior ventures in ocean exploration, cooperation is the only answer.
>
> I have instructed the Secretary of State to consult with other nations on the steps that could be taken to launch an historic and unprecedented adventure—an International Decade of Ocean Exploration for the 1970s.

The Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) supported the Decade idea and went on to endorse "an expanded, accelerated, long-term, and sustained program of exploration of the oceans and their resources, including international programs, planned and coordinated on a worldwide basis." Support also came from the U.N. General Assembly in December 1968; its Resolution 2467D (XXIII) endorsed "an international decade of ocean exploration to be undertaken within the framework of a long-term programme of research and exploration." The Assembly also invited member states "to formulate proposals for national and international scientific programmes and agreed [upon] activities to be undertaken during the international decade of ocean exploration, with due regard to the interests of developing countries, [and] to transmit these proposals to...the IOC in time to begin the decade in 1970."

At its sixth session in September 1969, the IOC defined the purpose of the expanded program thus: "To increase knowledge of the ocean, its contents and the contents of its subsoil, and its interfaces with the land, the atmosphere, and the ocean floor and to improve understanding of processes operating in or affecting the marine environment, with the goal of enhanced utilization of the ocean and its resources for the benefit of mankind."

Scientists and engineers looked at the many questions posed by this unprecedented effort. Attention focused on scientific and engineering priorities, how to realize them, and possible results and benefits of the IDOE. In May 1969 the National Academy of Sciences and the National Academy of Engineering jointly reported on a scientific planning conference in ***An Oceanic Quest, The International Decade of Ocean Exploration***. The report strongly recommended an IDOE and served as a basis for planning the Decade.

Responsibility for planning, managing, and funding United States IDOE activities went to the National Science Foundation. Major NSF goals were to:

- ***Expand seabed assessment activities***—for better domestic and international management of marine mineral exploration and exploitation—by learning more about seabed topography, structure, physical and dynamic properties, and resource potential. This would also help industry plan more detailed seabed investigations.

- ***Improve environmental forecasting*** and thus help reduce hazards to life and property and permit better use of marine resources. This would be done through improved physical and mathematical models of the ocean and atmosphere—models that would increase the accuracy, timeliness, and geographic precision of environmental forecasts.

- *Develop an ocean monitoring system* to help predict oceanographic and atmospheric conditions—through design and deployment of oceanographic data buoys and other remote sensing platforms.
- *Preserve the ocean environment* by accelerating scientific observations on the natural state of the ocean and its interactions with coastal areas. This would help scientists assess and predict ocean changes, whether natural or brought on by human activities. Scientists could also identify damaging or irreversible effects of waste disposal at sea and learn how various levels of marine life interact. This could prevent the depletion or extinction of valuable species as a result of human activities.
- *Improve worldwide data exchange* by modernizing and standardizing the way national and international marine data are gathered and used.
- *Accelerate Decade planning* to encourage international sharing of responsibilities and costs and to assure better use of limited exploration capabilities.

The National Science Foundation established the Office for the International Decade of Ocean Exploration in 1970 and received special funds from Congress for the United States IDOE program. Three areas were chosen for priority attention: (1) Seabed Assessment, (2) Environmental Forecasting, and (3) Environmental Quality. Living Resources was added as a fourth program in 1971.

IDOE Projects: Organization, Management, and Support

IDOE projects marked a significant departure from previous ocean science research. In the United States, that research was done primarily by individuals or small groups working in one of the four major subdisciplines (biology, chemistry, geology, physical oceanography). Most projects focused on relatively small problems in limited areas. There were indeed a few cooperative research efforts such as the International Indian Ocean Expedition in the early 1960s, but they were the exception rather than the rule.

The IDOE changed this by supporting large-scale, long-term research projects involving specialists from several disciplines. Thus IDOE projects were far larger and more complex than any before them. During the Decade, the National Science Foundation supported 22 major efforts at a total estimated cost of about $192 million. Individual projects ranged from about $1 million to more than $30 million and lasted from 3 to 10 years. Many involved joint support by other government agencies, principally the Office of Naval Research, the National Oceanic and Atmospheric Administration, and precursors to the present Department of Energy.

The projects stemmed from the scientific interests of the investigators, who also managed the various efforts. No single format or approach was required. Many of the large projects set up formal structures to handle ship scheduling, routine laboratory analyses, and intercalibration of instruments, and to ensure comparable techniques. Others had a less structured organization. Foreign scientists and facilities took part in most of the programs as full participants.

The long-term support for IDOE work permitted detailed planning for the projects and the necessary international contacts. A recurrent problem during the Decade was the long advance notice required for foreign scientists to arrange participation and funding. Clearance to allow research in foreign waters was also an occasional issue. IDOE's long-term support partially offset these problems, but U.S. funding cycles and management practices often did not match those of other countries.

Long-term support and detailed planning also boosted development of new equipment and instruments needed for the ambitious scientific undertakings. For example, sound-fixing and ranging (SOFAR) floats were developed to follow deep-ocean currents, much like the earlier Swallow floats. SOFAR floats were more cost effective: since they could be tracked from shore-based stations, no tracking ship was needed. Later, satellite-tracked surface floats provided comparable information for surface currents.

Finally, long-term support for IDOE projects helped ensure that the extensive field data were properly analyzed and widely distributed. A good example is the Geochemical Ocean Sections Study (GEOSECS), which resulted in the first modern chemical description of the ocean waters. Its data are the basis for many other ocean investigations. And they are a benchmark against which future generations will measure changes in the ocean due to either human activities or natural causes. GEOSECS data are published in atlases that bring together all the work, spanning more than 10 years, of the many investigators involved in the project.

Other efforts compiled existing data as a first step in further work. An example is the Manganese Nodule Project (MANOP). Its compilations on the abundance and composition of these nodules have focused attention on the possible mining of such materials from the deep-ocean floor.

The Nations in IDOE

The United States was one of 52 nations participating in the Decade research efforts. Many of the large projects were possible only because several countries pooled their scientists, equipment, ships, and other facilities. For example, MODE was a cooperative venture of the United States and the United Kingdom, while the ensuing POLYMODE was largely a joint effort of the U.S.A. and the USSR, with complementary work by Canada, France, West Germany, and the United Kingdom. Coastal upwelling research in the

Pacific was the joint work of Peruvian and American scientists, along with colleagues from other South American countries.

French and U.S. teams combined forces in the detailed surface-ship surveys and submersible dives that led to the discovery of active hydrothermal vents on the sea floor; Mexican scientists were involved in the RISE project that explored some of the eastern Pacific vents.

International cooperative projects have become an integral part of modern ocean science. Even now that the Decade has ended, oceanographers continue their joint exploration of oceans and their basins. Such projects are usually done under bilateral agreements between the United States and another country.

1. Seabed Assessment

Summary

The Seabed Assessment Program focused on geological, geophysical, and geochemical processes involved in ocean-floor dynamics and the formation of seabed resources. Substantial advances were made in understanding plate tectonics, the process that forms oceanic crust at the mid-ocean ridges or sea-floor spreading centers, then destroys the old crust at vast "subduction zones" or trenches, where it is resorbed into the underlying mantle. Also gained was a better understanding of how the chemical composition of seawater is affected by geological activity and how mineral-rich deposits form on the ocean floor.

Major advances came with the first use of manned submersibles for ocean-floor studies and direct measurements on the seabed. Beginning in 1974 with the French-American Mid-Ocean Undersea Study (FAMOUS), *exploration of the deep-ocean floor led to discovery of active, chimney-like vents discharging waters at 350 degrees Celsius (660 Fahrenheit). These discharges form massive deposits of sulfide minerals that are potentially valuable as a source of strategic metals. The deposits yield important clues about ore-formation processes; these in turn may be useful in searching for other such deposits on land and on the ocean bottom.*

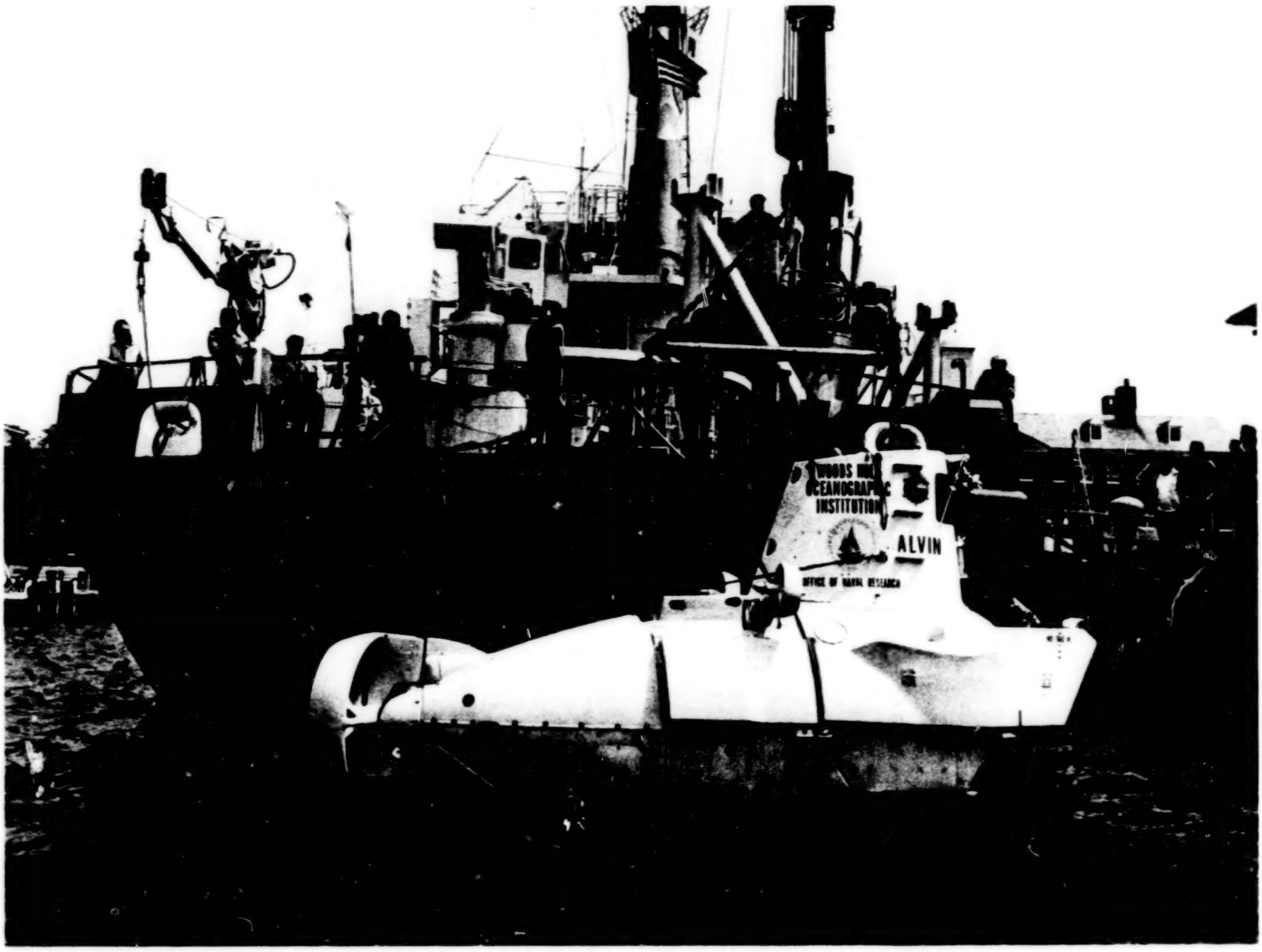
In addition, researchers aboard submersibles discovered previously unknown communities of large worms, clams, and other organisms. The complete absence of light at the depths where these organisms live indicates that bacteria, using the sulfides and metals discharged by the vents, form the base of the community's food web.

Other investigations of the Atlantic Ocean's continental margins sought to show how the South Atlantic was formed. Such studies mark the first stage in exploring for oil and gas in largely unknown areas. (The rich oil and gas fields of the North Sea and the Middle East come from areas geologically similar to the continental margins around the South Atlantic.) Another project mapped the distribution and composition of manganese nodules, potential sources of copper, nickel, and cobalt on the deep-ocean floor. Later studies focused on the processes forming these potentially important resources.

Most of the recent advances in understanding ocean basins have supported the theory of plate tectonics, the idea that the surface of the earth is formed by great crustal plates moving slowly but constantly in relation to one another. Where plates move apart, new oceanic crust is created in long undersea mountain ranges. Crust is consumed where these plates collide at deep-sea trenches. The constant movement of these crustal plates has resulted in the "drift" of continents on the earth's surface. As understanding of crustal plate formation and movement has grown, so has knowledge about the location and development of mineral resources in the ocean basins—supported, in part, by the Seabed Assessment Program.

Mining manganese nodules from the sea floor and producing large quantities of petroleum from the outer continental margin are still in the development stages. But the basic understanding of geologic processes and information about the oceanic crust that IDOE *scientists gained will be key factors affecting the use and regulation of these areas. At present, scientific understanding of these resources is running a bit ahead of the legal and institutional problems confronting their exploitation.*

Finally, Seabed Assessment researchers developed and built new automated instruments to make direct high-resolution measurements of ocean-bottom water and sediments. Previous technology required that samples be collected remotely and carried to the surface for analysis.



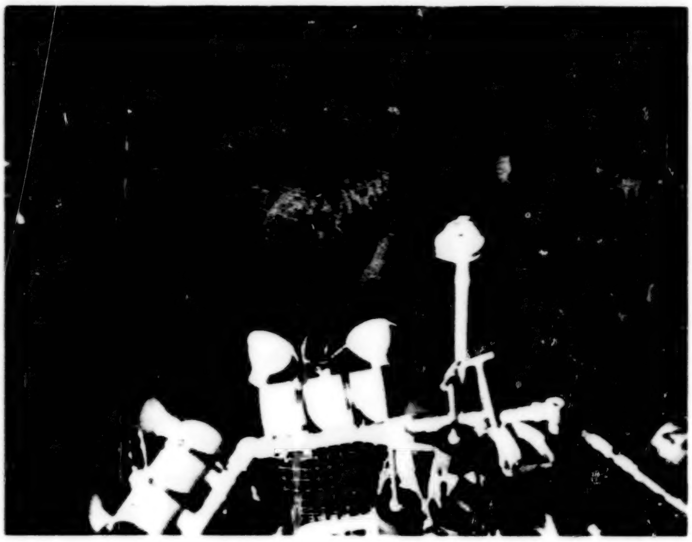
The deep-submergence research vehicle Alvin *is shown with the R/V* Knorr *at the Woods Hole Oceanographic Institution, before field operations of the French-American Mid-Ocean Undersea Study (project* FAMOUS*).* FAMOUS *gave earth scientists their first closeup look at the crustal plate.*

Project FAMOUS

This project looked at the geological processes creating ocean basins and was the first to use manned submersibles in scientific deep-sea research. Previous measurements of sea-bed conditions and collection of samples from surface ships had proved inadequate in revealing details about the sea floor.

Thirty dives in three submersibles took place in 1974 on the Mid-Atlantic Ridge during Project **FAMOUS** (French-American Mid-Ocean Undersea Study). The U.S. submersible *Alvin*, operated by the Woods Hole Oceanographic Institution in Massachusetts, worked with the French submersible *Archimede* and diving saucer *Cyana* in 2,700 meters of water southwest of the Azores. This area was chosen because of the continental plate activity there. The North American and European plates are moving apart at a relatively fast rate of 2 to 3 centimeters a year, as volcanic eruptions push molten material, or magma, up from within the earth to fill the void created by the diverging plates. (The underlying mechanism of plate tectonics is not yet clear. Before Project **FAMOUS**, scientists thought that the volcanic activity at these "spreading centers" might be pushing the plates apart. But **FAMOUS** data showed that the process is much more complicated.)

The most promising dive sites were chosen from studies of ocean-bottom charts based on detailed (multi-narrow-beam), echo-sounding data; ocean-bottom photographs; microearthquake locations; and heat-flow measurements, which are thermal indications of geological activity. The dives showed that the crest of the Mid-Atlantic Ridge has a fault-bounded central valley about 1 kilometer deep and 2 to 4 kilometers wide. Volcanic rock extrudes throughout the valley floor but is especially concentrated along a line of central volcanic hills. Systematic variation in the mineral composition of the lavas across the valley floor apparently reflects a zoning or chemical evolution of the magma under the rift valley. However, several lava flows with discrete geochemical characteristics may result from magma coming from the mantle and flowing into the chamber. Describing this compositional zoning of ocean-bottom lava was one of the most important contributions of the Project **FAMOUS** scientists; it has not been documented at any other location.



These "pillow" or "toothpaste" formations of lava result from rapid cooling of magma, or molten rock, as it extrudes at spreading centers. Alvin's arm and collection basket appear in this photo.

Geologists examine rocks newly dredged up from the Mid-Atlantic Ridge during Project FAMOUS. (*Photo by Michael Scofield*)

As in other spreading centers, the Mid-Atlantic Ridge at the Project FAMOUS site is broken into segments or fractures, each several tens of kilometers long and separated by large transform faults where the crustal plates move past each other. Two fracture zones were studied extensively through photography, dredging, and submersible dives. Researchers were surprised to see little evidence of recent faulting, although small earthquakes are frequent along the faults. Deposits resulting from hydrothermal activity were recovered from both fracture zones, but no discharge of hydrothermal water through active vents was observed there nor in the central valley.

Project FAMOUS played a critical role in revealing the processes active along oceanic ridges. First, it showed that detailed geological charting of rough, deep-sea terrain could be done by submersibles. Second, it helped identify major features of the sea-floor spreading process: a narrow, divided valley with an axial volcanic ridge fed by an underlying magma chamber. These essential features proved to be common to spreading centers in other areas, where faster spreading made them more difficult to recognize. More submersible exploration of these areas in the Pacific followed later in the Decade.

Nazca Plate Studies

Studies of the Nazca Plate in the eastern South Pacific began in 1971. Project scientists sought to add to present knowledge of plate tectonics by studying an oceanic plate from its origin at an oceanic rise or spreading center to its ultimate subduction in a trench beneath a continental margin. The Nazca Plate was an ideal setting for this study: its present western boundary is at the fast-spreading center on the East Pacific Rise, and its eastern boundary is in the deep Peru-Chile Trench.

A second goal, which received added emphasis during the project, was to relate the formation of metal-rich deposits, or metallogenesis, to tectonic processes along the plate margins. Studies concentrated on the East Pacific Rise, where extensive deposits of metal-rich sediments were known to occur, and across the Peru-Chile Trench. Here researchers tried to learn the processes by which oceanic crust and accumulated sediments subduct and contribute to the formation of rich ore deposits in the nearby, and geologically related, Andes mountains.

The lead scientists were from the Hawaiian Institute of Geophysics and Oregon State University. Also involved were researchers from the National Oceanic and Atmospheric Administration (NOAA) and scientists from Bolivia, Canada, Chile, Colombia, Ecuador, Peru, and the USSR.

Extensive field studies took place between 1972 and 1977. The shipboard work and subsequent laboratory analysis involved bathymetry, heat flow, dredging, coring, and seismic profiling. Extensive geochemical analyses were done on sediment and rock samples from the plate. And a number of highly detailed surveys were undertaken along the East Pacific Rise and across the Peru-Chile Trench.

The trench surveys were highlighted by the first use of the multichannel seismic profiling system in an academic, basic research project. This system, developed for oil company exploration, allows for deeper penetration and higher resolution of sedimentary strata beneath the ocean floor. It helped scientists study deformation of sediments and crustal rocks just before subduction, deep below the South American margin, where echo-sounding systems normally used are of little value.

Nazca Plate scientists and others have been able to trace a complicated history for the area. Using the extensive sediment collections from the project, geochemists identified potential sources of metal-rich sediments across the plate. Near the East Pacific Rise, sediments are dominated by volcanically derived material. It is produced by hydrothermal circulation of seawater through the oceanic crust and the later precipitation of material in the near-bottom waters. The growing realization of how important this process is in marine metallogenesis led to other vent studies described in this report.

Faulting, or nonuniform breaking of the crustal plate, begins far westward of the plate's eastern boundary. Near the Peru-Chile Trench, researchers discovered evidence for uplift and subsiding of this faulted material. Further multichannel investigations beneath the South American margin showed that the processes causing these movements are tied to processes on the adjacent continental plate. Both uplift and subsiding relate to subduction along the trench; how these processes are linked to mineral deposits in the Andes is a subject for ongoing research.

Major scientific results of this project are in a memoir published in 1981 by the Geological Society of America and entitled: "Nazca Plate, Crustal Formation and Andean Convergence." Like other IDOE studies, the project collected much valuable data and their interpretation has spawned interest in future research.

Studies In East Asia Tectonics and Resources (SEATAR)

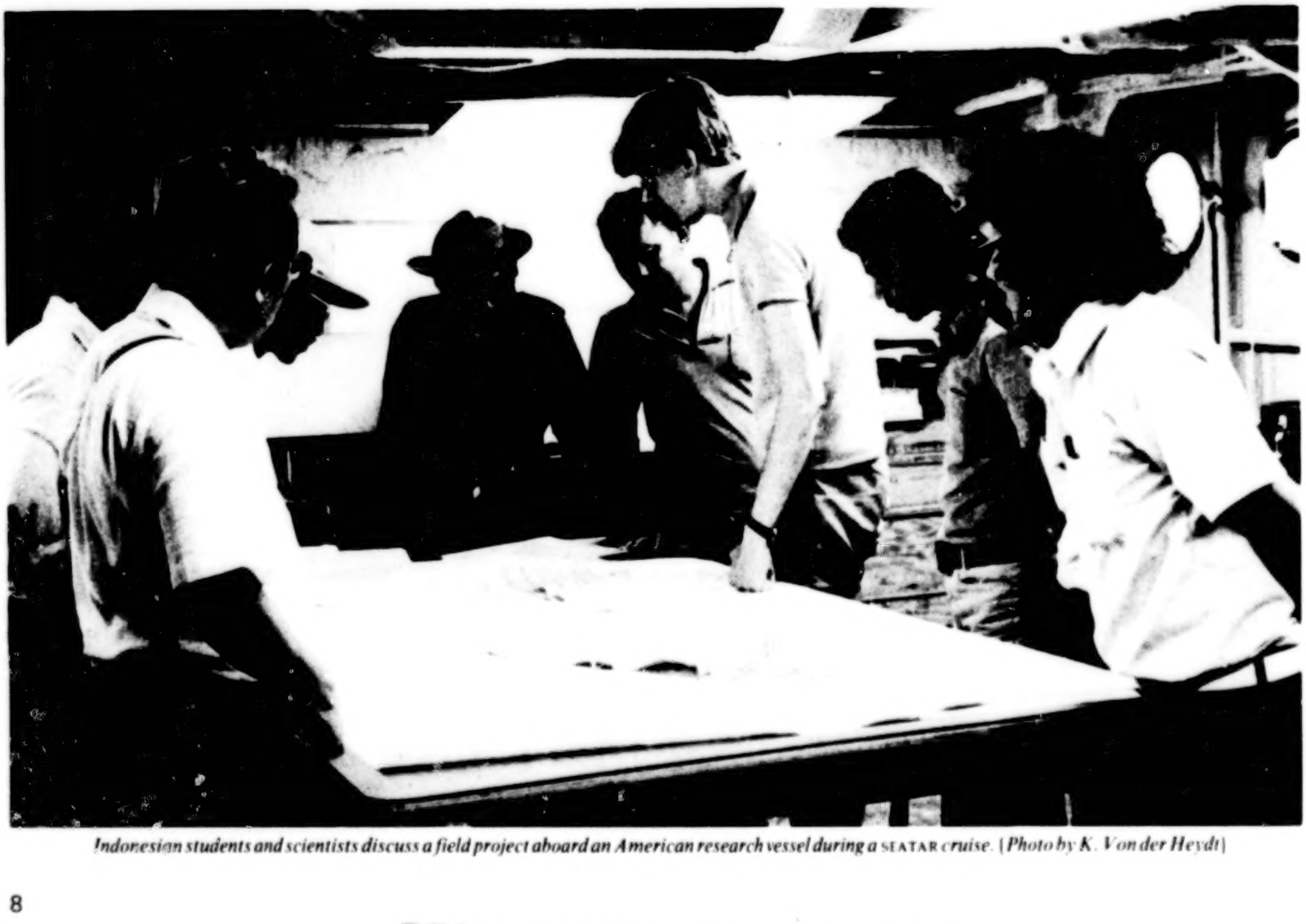
This project also studied plate tectonics. But rather than looking at plate margins along a deep trench, as Nazca Plate researchers did, SEATAR focused on another type of margin where plates converge and collide with one another to form island arcs. Geological processes in these convergent zones are also very complex and are important to our understanding of how continental crust is formed and how mineral and hydrocarbon deposits accumulate.

SEATAR began in 1974, after recommendations of a workshop sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO. Although U.S. scientists played the largest role in SEATAR, there was substantial participation by scientists from East Asia (including Indonesia and Japan) as well as the Federal Republic of Germany and, to a lesser extent, Great Britain and Australia. SEATAR investigators were concerned with basic research into geological processes and the resource potential of those processes.

In its simplest form, subduction of an oceanic plate in a convergence zone involves relatively denser crust descending into the earth's mantle, under a less dense plate. At depths of about 90 to 100 kilometers, the subducting layer breaks up and is eventually incorporated into the mantle. Melting of the subducted materials forms magmas that rise toward the earth's surface. There some erupt as volcanoes, eventually forming island arcs.

Other magma bodies erupt in back-arc basin spreading centers. These processes mobilize metals that create ore-grade deposits of chromium, copper, and iron. The molten lavas also superheat ocean-bottom water, which dissolves other metals. These metal-rich waters later produce sulfides of copper, nickel, and iron. All this helps fashion continental crust, a major study area in geoscience.

In the region between the volcanic island arc and the deep-sea trench, sediments accumulate in the fore-arc basin. The resulting masses, approaching 4 kilometers thick, are



Indonesian students and scientists discuss a field project aboard an American research vessel during a SEATAR cruise. (Photo by K. Von der Heydt) favorable sites for hydrocarbon formation and accumulation. SEATAR's main objective, then, was to understand the processes acting along the island arcs, deep-sea trenches, and back-arc basins—and the role of those processes in ore formation and hydrocarbon accumulation.

The system of island arcs, trenches, and back-arc basins is simplest in the Mariana Islands of the Western Pacific. SEATAR research focused on this area to interpret other island-arc systems in more advanced stages of development. The Indonesian archipelago and Java Trench, which constitute the Sunda Arc, had long been a testing ground for theories of island arc-trench evolution. The Philippine archipelago is a complex of island-arc systems coalesced into something approaching a continental mass. Ultimately chosen for detailed study were four geographical areas, each representing a different stage of tectonic development: the Mariana, Philippines, Banda, and Sunda arcs, all of them rich in mineral and hydrocarbon resources.

SEATAR investigators carried out a large-scale interdisciplinary study. Shipboard and land-based field programs and subsequent laboratory work focused on natural seismicity and marine geophysics, and on petrologic and geochemical study of rocks and sediments dredged from the sea floor and islands. These data were supplemented by deep cores from the drill ship *Glomar Challenger*. Detailed analysis was made of currently active tectonic processes that cause the subduction of oceanic crust, island-arc genesis, and the development of marginal basins. From this work, scientists have been able to understand the processes responsible for older, inactive tectonic processes.

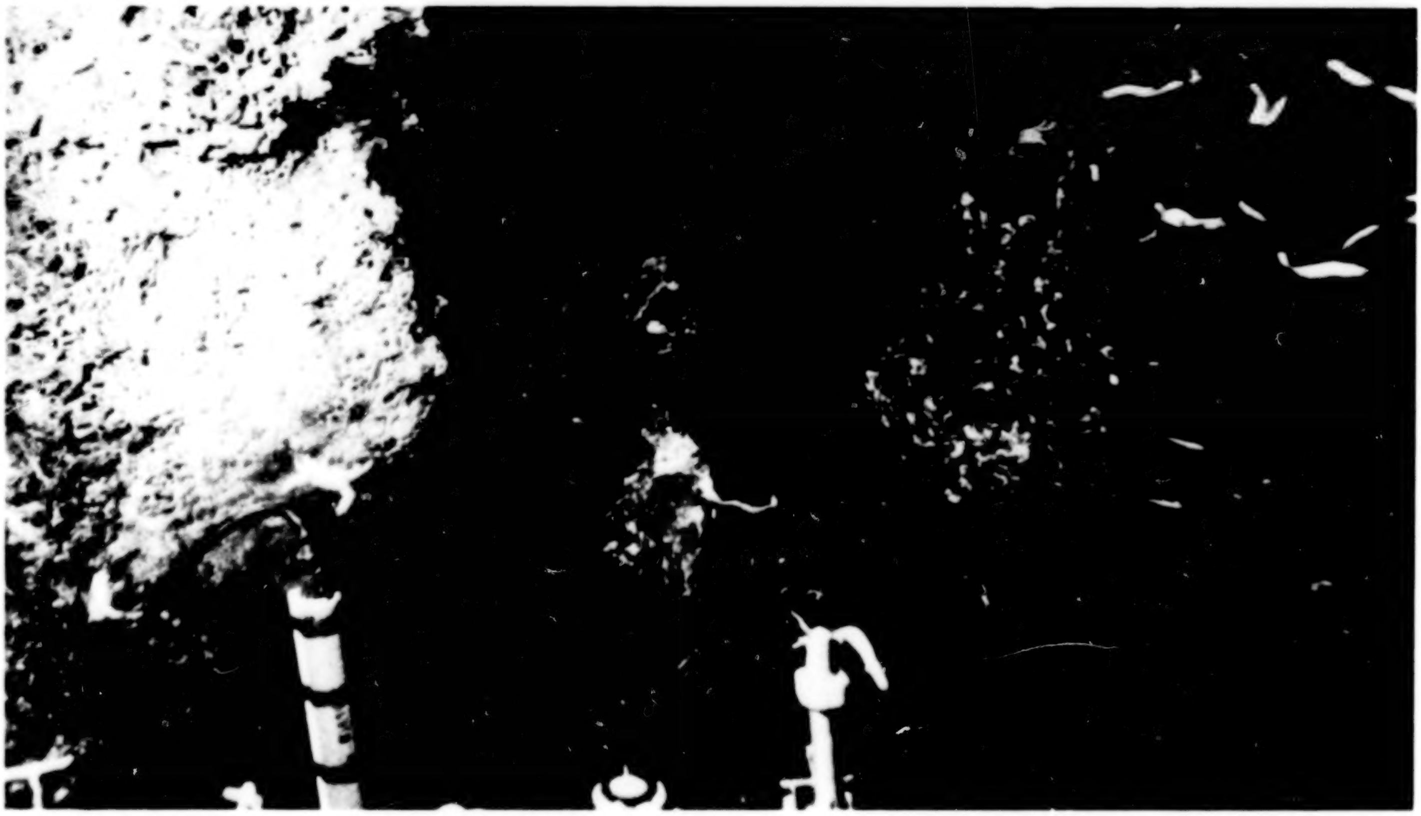
SEATAR scientists fulfilled a main goal of the Seabed Assessment Program: to permit better domestic and international management of marine mineral exploration and exploitation. They did this by acquiring knowledge on seabed topography, structure, physical and dynamic properties, and resource potential. Such knowledge will help industry plan more detailed investigations in this field.

To achieve this goal, investigators focused on a complex of arcs, trenches, and back-arc basins where the processes of time and space can be defined and studied. The region is known to be rich in mineral deposits and hydrocarbons, so the level of knowledge is already greater than for similar areas. The existing data base, however, was fragmented and needed a broad regional framework for appropriate work to be done.

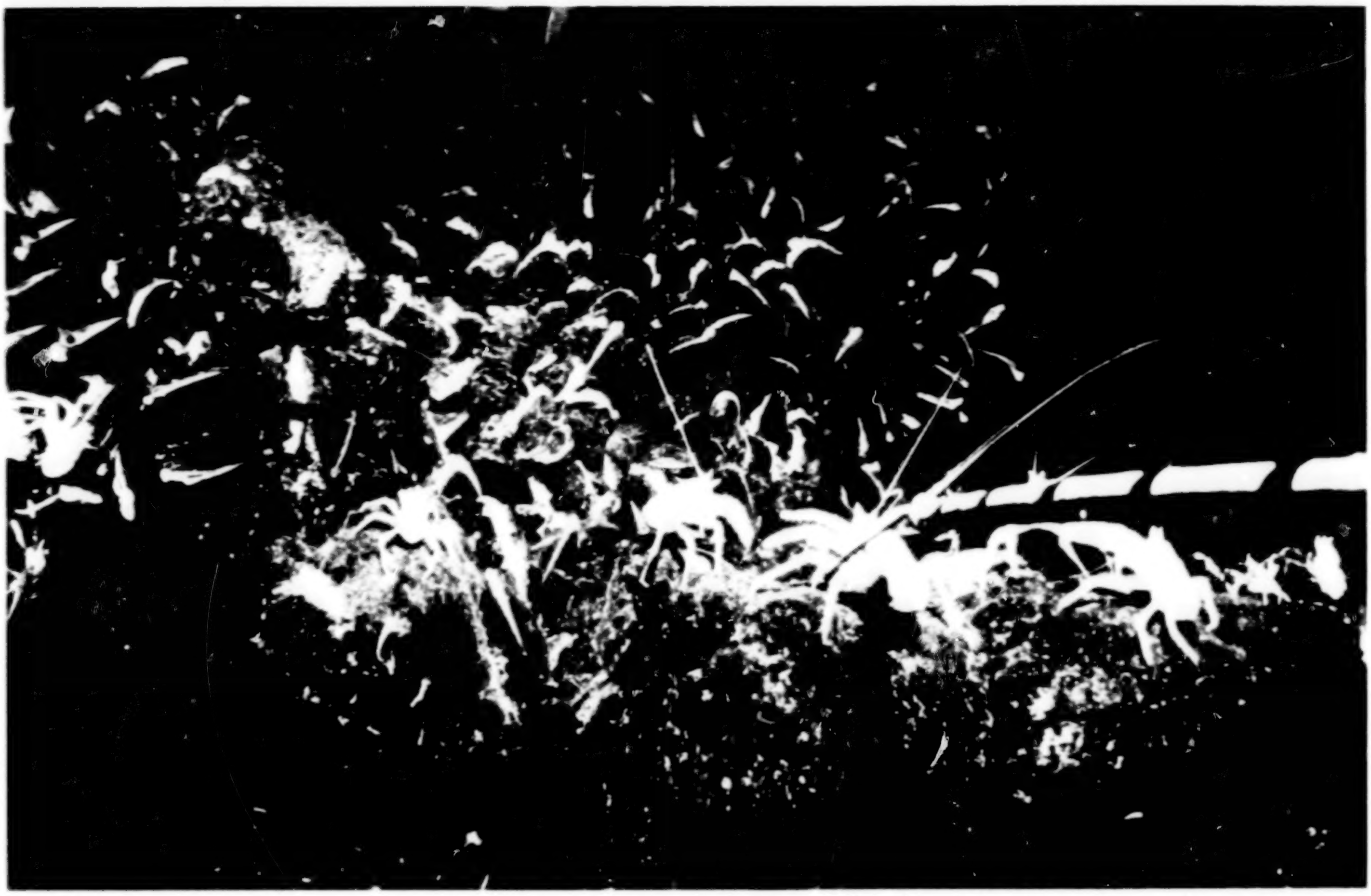
A long list of scientific publications has come from SEATAR studies; they give detailed interpretations of plate tectonics and mineral accumulation. Geophysical and bathymetric (depth) data have been published in a format useful to the scientific community. A 6-map atlas of the SEATAR area has been published by the Geological Society of America. Many scientific papers have appeared in refereed journals and have been presented at national and international scientific meetings.

Galapagos Rift and East Pacific Rise Studies

Scientists had long speculated, but were unable to confirm, that metallic deposits on the sea floor were formed by hydrothermal vents associated with recent volcanic activity.



When scientists tried to measure the temperature of the water emitted from vents such as this, the temperature probe on Alvin melted. Temperatures were found to be in excess of 350 degrees Celsius (660 F.). These vent waters may be a valuable source of strategic metals. (Photo by Dudley Foster)



A community of unusual animals were found around warm-water vents on the Galapagos Rift in an otherwise barren seascape. These animals [illegible] distant relative of the man-o-war jellyfish; mussels, crabs (top), and tube worms (bottom). [illegible] the first known chemosynthetic food chain based on sulfur-oxidizing bacteria that [illegible] Robert Hessler and Jack Donnelly

R[illegible] FAMOUS [illegible] of this speculation. [illegible] Seawater was thought [illegible] would then be heated to [illegible] the form of hot springs. [illegible] would cause [illegible] metallic compounds [illegible] rapidly cooling [illegible] Confirmation [illegible] radiometrically [illegible] the importance of [illegible]

[illegible] Rise. [illegible] spreading faster [illegible] Mid-Atlantic Ridge [illegible] thought to be one of [illegible] expeditions [illegible] While others systems [illegible] B[illegible] emphasized [illegible] hydrothermal [illegible] 1000 [illegible]

Galapagos Rift in 1977 and on the East Pacific Rise in 1979. The latter expedition was [illegible] French, Mexican, and American [illegible] mouth of the Gulf of California.

[illegible] the East Pacific Rise [illegible] Mid-Atlantic Ridge, and [illegible] seismic [illegible] second [illegible] up to [illegible] across

The chimneys are composed of silica and metal sulfides, including copper, nickel, cadmium, and sulfur. These deposits are leached from the rocks and precipitated by ejected water measured at temperatures as high as 350 degrees Celsius. The vents occur in clusters and narrow bands about 250 meters across and several kilometers long. Similar deposits of these minerals exposed on land have long been mined on Cyprus and in Japan. Further investigations and return expeditions have been planned during the 1980s and beyond.

In addition to the geological importance of the vents, there was an unexpected biological bonus: extraordinary communities of animals were found clustered around the vents. This was in sharp contrast to the sparsely populated surrounding seascape, and the discovery has spawned a whole new area of biological research. This represents the first known ecosystem based not on photosynthesis but on chemosynthesis, using hydrogen sulfide exuded from the vents. Bacteria metabolize the hydrogen sulfide in the water ejected from the vents and multiply, creating the primary food source for higher organisms.

The 1977 Galapagos expedition won an award from the American Association for the Advancement of Science and was featured in a National Geographic television special, first aired in January 1980. The work also generated further chemical and biological investigations of these hydrothermal areas that should continue into the 1980s and beyond.

Continental Margins of the South Atlantic Ocean

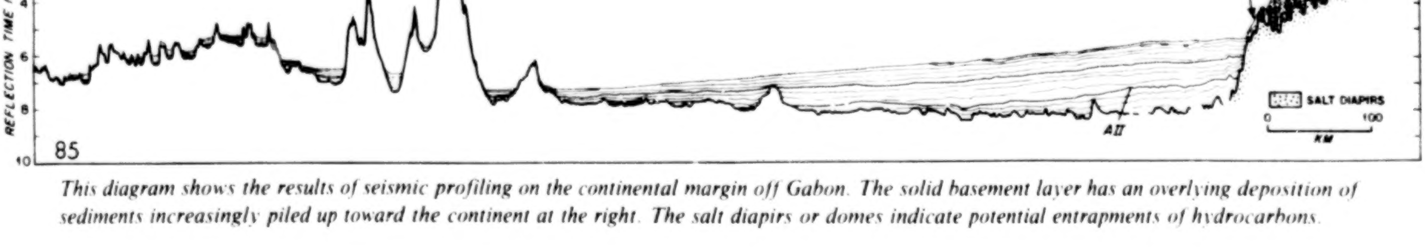
An early IDOE project was a study of the "passive" continental margins in the South Atlantic, with emphasis on conditions that offer favorable circumstances for hydrocarbon accumulation. The mid-plate Atlantic margins were formed as the ocean basin opened. Relatively little happens there geologically, compared to the volcanically and tectonically active Pacific margins where crustal plates are converging. The South Atlantic was selected because it displayed the best fit between two continents. The breakup of an earlier supercontinent, known as Gondwanaland, is thought to have formed the present continents of Africa and South America and to account for the striking fit of the South Atlantic margins. The geological structures of the two continents also fit. Some of the elongated sedimentary basins that run along the South Atlantic coastlines contain large oil fields, notably in Brazil and Nigeria.

A scientist from the Woods Hole Oceanographic Institution plots geophysical data aboard R/V Atlantis II *with two scientists from Ghana during survey work on the continental margins of the South Atlantic.*

As Africa and South America moved apart, the shallow basin between them presented ideal conditions for oil formation. By studying both sides of the present ocean basin, the stages of continental separation could be followed and events unique to one side or the other could be better understood. The Woods Hole Oceanographic Institution concentrated on the west coast of Africa from Capetown to Lisbon, and the Lamont-Doherty Geological Observatory of Columbia University worked on the east coast of South America from the Scotia Arc to the Caribbean.

Underway, shipboard geophysical observations (seismic reflection, sonobuoy, refraction, gravity, and magnetics) were made from the Mid-Atlantic Ridge to the continental margin. There a thick wedge of sediments, basic to hydrocarbon formation, obscures the basement reflection. Both the Woods Hole and Columbia groups cooperated with Brazilian scientists on a two-ship seismic refraction study of the Amazon Cone. Researchers from Argentina, Brazil, and several African countries participated in scientific cruises and data analyses; these countries also provided extensive logistical support.

IDOE scientists were able to reconstruct the opening of the South Atlantic, revealing evidence of tectonic activity there—for example, the initial rifting (breaking apart along large faults) of the continents, their drifting apart, later subsiding of the newly formed basin floor, and sediment deposit in the new ocean basins.



This diagram shows the results of seismic profiling on the continental margin off Gabon. The solid basement layer has an overlying deposition of sediments increasingly piled up toward the continent at the right. The salt diapirs or domes indicate potential entrapments of hydrocarbons.

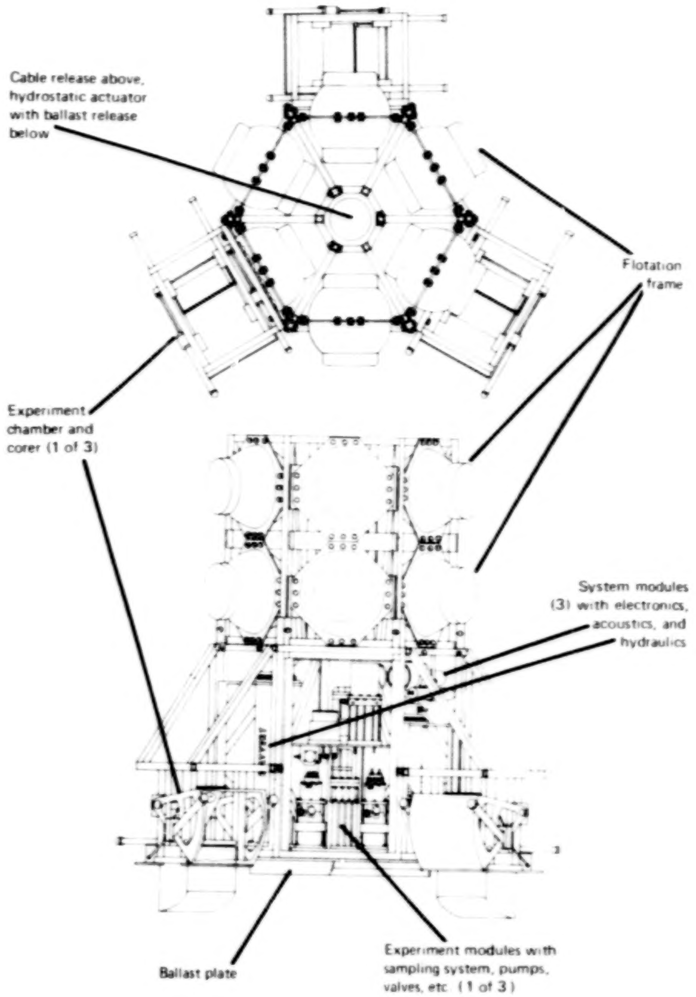
As the continents pulled apart, large basins formed and filled with sediment, especially near major river systems such as the Niger, Congo, and Amazon. As basement subsiding continued, marine sediments collected at the bottom of the restricted shallow sea, much like the Gulf of California. Where these basins were isolated in warm climates, large amounts of seawater evaporated and thick salt deposits formed. On the sides of these basins, carbonate sediments accumulated and reefs grew. Thus potential reservoir beds—porous, buried reefs and domes created above the salt beds as sediment layers shift over time—were formed near petroleum source rocks (carbon-rich sediments in the restricted basins). These are highly favorable conditions for accumulations of oil and gas. Similar conditions formed the huge oil fields of the Middle East. Another potential site for hydrocarbon formation: thick deposits from the slumping of sediments in deep-water areas in front of major deltas.

Manganese Nodules

Another early project under Seabed Assessment was an investigation of the origin and distribution of manganese nodules and the processes by which they selectively concentrate copper and nickel. In 1972, spurred by the late Maurice Ewing of Columbia University, a workshop/symposium was held to learn the extent of knowledge on this subject and to recommend a program of research. More than 100 scientists from industry, universities, and government participated, including many from foreign nations. Workshops covered scientific research, environmental impact, deep-sea mining technology, and the economic and legal implications of such mining. Later IDOE work emphasized research on the basic scientific questions of nodule formation and distribution.

Researchers assembled all available data from core laboratories, data banks, and files. They then put out widely distributed maps of the metal content and distribution of nodules over the world's oceans. The north-central Pacific (near the Hawaiian Islands) was identified as the zone where the nodules have the highest copper, cobalt, and nickel content.

One IDOE project looked into the mysteries of manganese nodule formation and distribution. Some estimates indicate that 25 percent of the sea floor is covered with these ore-bearing nodules.


Cable release above, hydrostatic actuator with ballast release below
Flotation frame
Experiment chamber and corer (1 of 3)
System modules (3) with electronics, acoustics, and hydraulics
Ballast plate
Experiment modules with sampling system, pumps, valves, etc. (1 of 3)

This schematic diagram shows the bottom lander, designed to make long-term measurements of metal concentrations in sediment waters and of the chemical dynamics of dissolved metals at the sea floor.

Further exploration revealed a broad picture of the conditions under which nodules form. But the process concentrating specific metals is still under investigation at this writing and is open to various interpretations. At present researchers are pursuing this question through long-term, onsite measurements of interactions between ocean-bottom water and adjacent sediments. A remote-controlled experimental vehicle called a bottom lander was developed to make these measurements. Sites for using the lander will be in each of the five major sedimentary provinces of the Pacific: siliceous ooze, calcareous ooze, metalliferous sediment, hemiplagic clay, and red clay. Contrasting evidence from areas where metal contents differ in kind and amount will add to present knowledge about nodule formation.

Analysis of IDOE work on manganese nodules will continue into the 1980s. Sufficient groundwork was laid for continuing research by other agencies and by private firms interested in harvesting these mineral-rich deposits.

Cenozoic Paleoceanography Project

This interdisciplinary IDOE project, begun in 1978, grew out of several smaller individual efforts. Its goal was to develop a comprehensive understanding of ocean evolution during the middle and late Cenozoic periods of geologic history (the last 25 million years). This time period spans the earth's transition from essentially an ice-free state to one marked by fluctuating ice caps.

Some parts of the ocean floor contain sediments that have accumulated from the early Cenozoic period. Use of radio isotopes enables scientists to date the deposition of each sedimentary layer. With this dating process, along with a detailed study of the fossilized remains of organisms in this sedimentary material, scientists hope to learn about ocean circulation, the distribution of organisms, and the chemistry of the Cenozoic oceans. The prime source of information: sediment cores from the Deep-Sea Drilling Project, sponsored in part by the National Science Foundation. Supplemental sources were cores and samples from exposed marine sediments on land.

Much of the project's early work was spent developing quantitative micropaleontological techniques. Among these were methods to resolve the taxonomy of microfossils, for comparisons between oceans, and procedures to analyze the chemical composition of microfossils. Investigators will develop a series of maps depicting water temperature and major currents in the oceans, major climate features, and the distribution of marine life for two time periods. The first period, about 17 million years ago, will show ocean conditions before the onset of glaciers in Antarctica. The second will show conditions about 6 million years ago, after the formation of the Antarctic ice cap but before glaciation in the Northern Hemisphere.

Data analysis is ongoing at this writing, but an early discovery was the decrease in the amount of carbon-13 in fossils from about 6.2 million years ago. This profound change in the carbon isotope content of bottom-dwelling organisms shows an alteration in the chemical composition of their environment. That in turn indicates either a significant change in the chemical composition of the oceans or a change in water circulation about that time. An explanation for this difference in water chemistry over 6 million years ago is being formulated, and valuable information on the origins of the oceans will result from the final analyses of this project.

2. Living Resources

Summary

IDOE's Living Resources Program supported projects to investigate two ocean ecosystems: the extensive seagrass areas that border many of the world's coastlines, and the coastal upwelling systems, characterized by extremely high marine life productivity and rich fisheries.

Seagrasses are widely dispersed around the world. They provide a habitat for many organisms, shelter both adults and their larval forms, support seabirds, and protect coastal areas from erosion. Two sites were the primary focus of the Seagrass Ecosystem Study (SES)*: St. Croix in the Virgin Islands and Izembek Lagoon in Alaska. Two cruises of the research vessel* Alpha Helix *extended the range of this work into other areas.*

SES *studies showed that dredging poses the greatest threat to valuable seagrass resources by directly destroying substrates, the base on which the grasses grow. Turbid waters caused by dredging and waste disposal operations kill seagrasses, leading ultimately to loss of recreational fisheries valued in the millions of dollars. Discharges of heated waters from power plants and other sources also destroy seagrass beds in tropical areas.* SES *scientists developed methods to transplant seagrasses to reestablish beds damaged or destroyed by natural processes or human activities.*

The Coastal Upwelling Ecosystems Analysis (CUEA) *investigated coastal upwelling (the upward flow of deep, nutrient-rich water) and its biological consequences off Oregon, Mexico, northwest Africa, and Peru. Researchers studied the effects of local winds on currents and on the nutrients needed for phytoplankton and zooplankton (free-floating, microscopic plant and animal communities, respectively). These studies were then combined into a comprehensive picture of upwelling processes and the responses of marine organisms to them. From this work, scientists learned to predict how upwelling systems respond to different atmospheric and ocean conditions.*

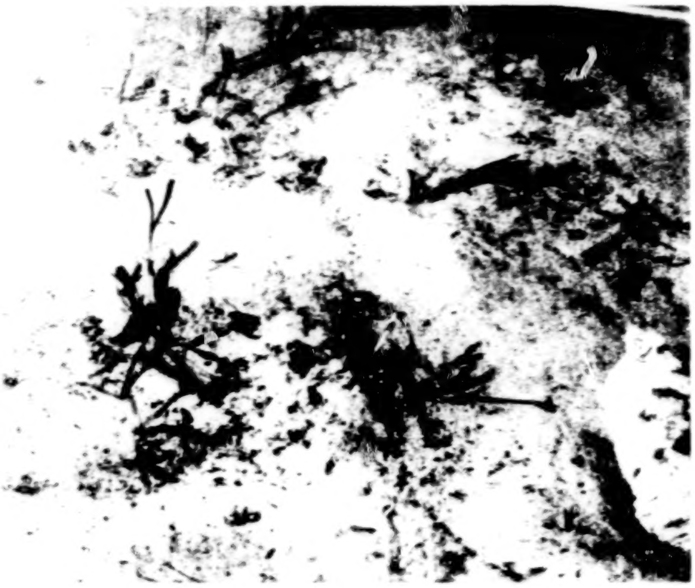
Seagrass Ecosystem Study (SES)

There are few parts of the world's coasts where seagrasses do not grow. Seagrass meadows are among the most productive natural ecosystems on earth, and they support a wide variety of marine life. A few scientists have studied seagrasses, but their work has generally fallen somewhere between that of freshwater biologists and biological oceanographers. Thus this vital area had been somewhat shortchanged.

Scientists hoping to fill this gap first met in 1973 at the University of Alaska and later that year at Leiden, The Netherlands, to plan seagrass ecosystems studies. Three questions have guided the SES work: (1) What do seagrasses contribute to food webs, nutrient and mineral recycling, and coastal stabilization? (2) What processes sustain seagrass ecosystems, and how are they affected by environmental changes or disturbances, either natural or artificial? (3) What structural patterns in seagrass ecosystems allow them to maintain their stability?

SES was organized by 11 investigators from 9 U.S. institutions who had been in regular contact with colleagues in France, Mexico, Denmark, and Japan. A network of experimental sites was studied. The two primary ones were at St. Croix, U.S. Virgin Islands, and Izembek Lagoon, Alaska, with other intermediate sites and laboratory studies giving supplemental information. In addition, cruises on the R/V *Alpha Helix* to Mosquito Keys in the Caribbean and to the reefs between New Guinea and Australia extended the range of the study. SES researchers obtained baseline information on the biological structure, function, and development of seagrass ecosystems in northern, temperate, and tropical regions. They also observed year-to-year variation.

Previous work had been largely descriptive, so a major task of the first phase of SES was to develop techniques for long-term studies. Among these were methods for sediment-chemistry and nutrient-cycle studies, as well as transplant techniques. Patterns and processes of nutrient cycling, productivity, and food-web dynamics have now been identified and used to test hypotheses on seagrass ecosystem development. Resulting models predict short- and long-term



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ping off the bacteria, protozoa, and epiphytic algae. Juvenile fish, crabs, shrimp, and other species in turn eat the snails, worms, amphipods, and in some cases the detritus as well. Finally, adult fish swim in on the high tide to feed on juvenile fish, shrimp, and crustaceans. Some detritus drifts away on the ebbing tide to provide nutrients for invertebrates and fish in nearby areas.

Seagrasses are also important because they anchor sediments and detritus deposits against wave and current action. In addition, by absorbing the force of waves and currents during storms, seagrass beds greatly reduce shoreline erosion and act as a buffer to protect bays, estuaries, and coastlines.

SES scientists found that dredging poses the greatest threat to seagrass beds by increasing turbidity (conditions prohibiting light from passing through water) and thus reducing photosynthesis. One study found that dredging and filling in Boca Ciega Bay, Florida, caused destruction of 1,100 tons of fish. The loss in revenues from water sports and fishing was estimated in 1968 at $1.4 million.

Thermal pollution is another threat to seagrasses. In Biscayne Bay, Florida, hot water discharged from a nuclear plant destroyed nearby turtle grass beds. Effects of chemical pollutants are less clear, but grasses appear to be relatively resistant to toxic substances that poison other marine life. Sewage effluents can act in different ways: too many can kill directly or cause algae blooms that cut off essential light, but a moderate amount apparently stimulates growth. The plants can store up material such as manganese, zinc, and iron without serious damage, at least up to a certain point, but these substances may then be passed up a food chain.

The potential economic benefits of using seagrass transplants to reduce shoreline erosion are enormous. The Dutch, for example, have developed artificial seagrasses for this purpose.

Coastal Upwelling Ecosystems Analysis (CUEA)

Changes in the upwelling or rising of deep, nutrient-rich waters in coastal areas have had major social and economic impacts on countries using fisheries supported by the upwelling. An example is the El Niño event off the coast of Peru, a periodic infusion of warm water described under **NORPAX** in the Environmental Forecasting section of this report. Whereas **NORPAX** looked at the physical causes of El Niño, **CUEA** scientists looked at its ecological consequences. Early work on coastal upwelling systems, by June Patullo at Oregon State University in the early 1960s, suggested that physical processes were directly responsible for the high productivity of plants and animals in these areas. But the fundamental idea of **CUEA**—that upwelling ecosystems are a single, tightly connected physical and biological process—was still controversial in 1970.

CUEA scientists sought to predict the biological productivity of an upwelling system by observing critical air/sea processes, mainly wind and currents. While physical processes were thought to be most important, the initial concept also included biological activities that affect phytoplankton. Among these are grazing, predation, sinking, and nutrient regeneration by zooplankton, fish, and animals living on the ocean bottom.

Phytoplankton forms the base of the food web that supports commercially important fish, so the CUEA scientists postulated that understanding phytoplankton dynamics was necessary for rational management, use, and conservation of fisheries resources in upwelling systems. They knew that living resources heavily exploited or stressed by pollution are most vulnerable to natural changes in the environment.

Four research objectives were the core of the CUEA plan: (1) describe the major factors in the upwelling system, including radiation, wind, currents, water density, nutrients, phytoplankton, zooplankton, nekton (free-swimming animals), and benthos (organisms living on the ocean bottom); (2) identify and measure physical, chemical, and biological processes; (3) document links between physical and biological processes that combine in coastal upwelling ecosystems to increase productivity at least tenfold over that of other oceanic regions; and (4) develop techniques to predict the responses of these ecosystems to upwelling variations.

CUEA scientists documented the complete upwelling process from atmospheric wind-driven forcing of the sea surface to the physical and biological responses of the ocean. This required simultaneous operation of shore-based meteorological stations, moored current-meters, aircraft, and research vessels by 25 investigators from 1 Peruvian and 13 American institutions. In the African and South American studies, two West German institutions worked with ships and current-meters.

Two major field expeditions combined the experience of four earlier and smaller field projects. The first took place from February to May 1974 off northwest Africa, where there is a wide continental shelf with upwelling primarily at

A current-meter used for coastal upwelling studies is readied for launch.

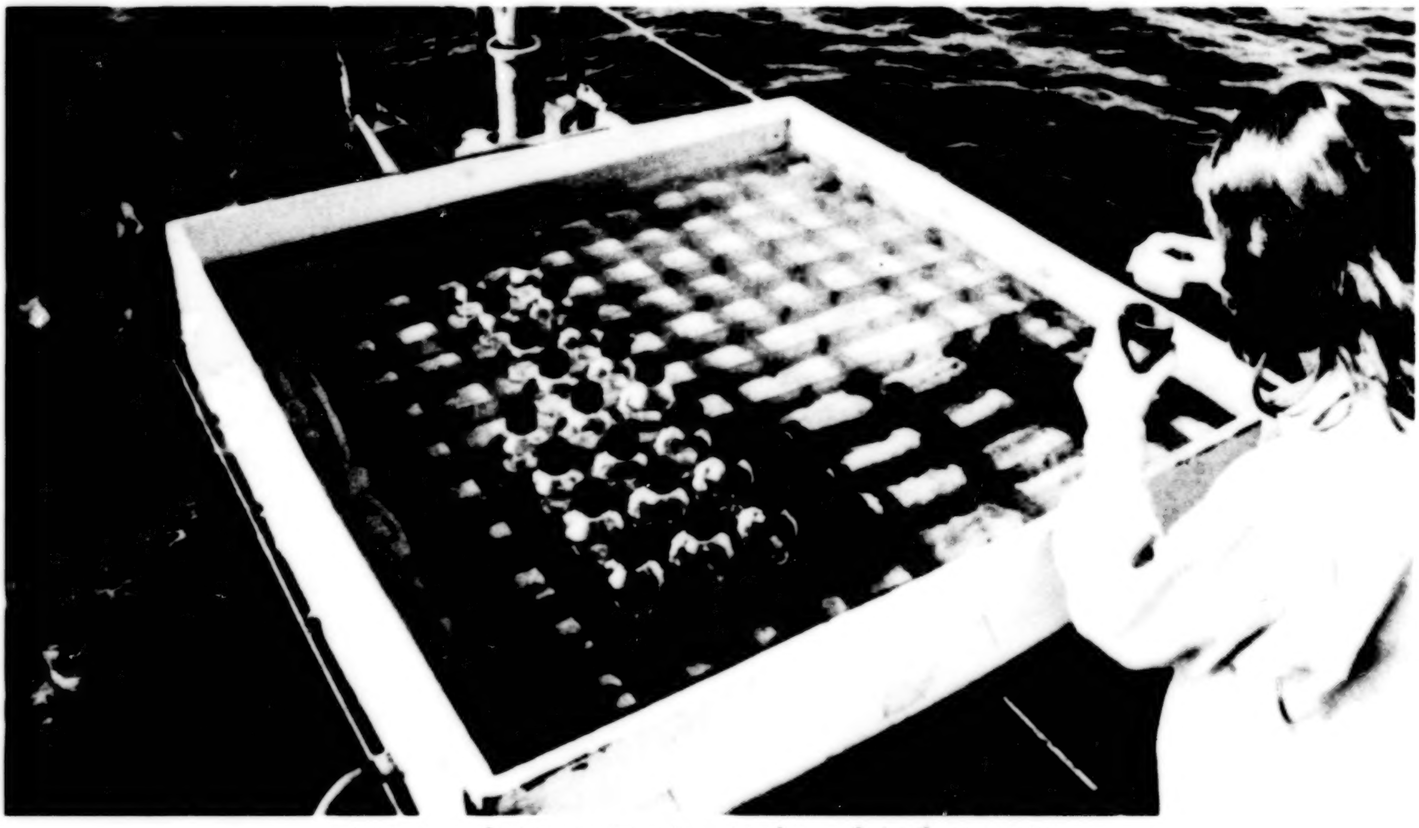
the shelf break. Ships, aircraft, equipment, and scientists from eight countries were involved. A second major expedition was a United States and Peruvian effort off the western coast of South America at 15 degrees south longitude during March-May 1976, July-November 1976, and March-May 1977.

Analysis of CUEA observations continues, but scientists did identify the physical and biological coupling of ocean conditions in upwelling systems. Now, given any coastal upwelling area and with knowledge of its shelf width and latitude, oceanographers can predict how variations in local winds will affect primary productivity, or photosynthetic production of plants. For example, off northwest Africa at the latitude of Cape Verde or Dakar, primary productivity increases with storm frequency. Storm-driven forces on the ocean cause nutrient-rich water to well up and mix with surface coastal waters that are usually characterized by frequent periods of nutrient depletion. Farther north near Cape Blanc, where wind and ocean-bottom topography differ, the opposite occurs: increased storm frequency decreases productivity. This knowledge enables scientists to predict alterations in phytoplankton productivity and composition, and hence fish stocks, caused by changes in local winds.

Researchers on CUEA expeditions to the Baja California coast in 1972 and 1973 learned how weak, early stages of upwelling can trigger blooms of one particular type of phytoplankter (a phytoplankton organism) called dinoflagellates, and how strong winds and upwelling bring on conditions that replace them with another type called diatoms. This succession of plankton type has been described to the point where preliminary predictions of phytoplankton composition are possible. The importance of these predictions is underscored by recent work showing that certain fish larvae, in the critical period when they first start to feed, must have dinoflagellates of a certain size and concentration to grow and survive; diatoms alone will not suffice.

CUEA researchers have also documented and successfully modeled wind direction and intensity in upwelling processes. Periods of strong winds favorable to upwelling, interrupted by a few days of slack winds, vary on time scales characteristic of a particular region. For example, off the coast of Oregon strong, sustained winds last several days to a week, while off northwest Africa and Peru they last one to several weeks. Phytoplankton growth rates are closely linked to these wind events, as are large fluctuations in the currents over the continental shelf and slope. Changes in zooplankton composition in the mid-shelf region off Peru are also heavily influenced by changes in surface currents. Transport of the upwelled waters is a key to determine what species of phytoplankton and zooplankton persist in the upwelling ecosystem.

A relatively narrow band fewer than 50 kilometers across delineates the area where upwelled and surface water mix. Shelf and slope topography clearly influence the locations of intense upwelling. Off northwest Africa, the shelf is wide and the slope very steep; there the coldest surface waters, indicating upwelled water, occur just inshore of the shelf break or where depth sharply increases. In contrast, off Oregon and Peru, the shelf is relatively steep and narrow; there, the most intense upwelling occurs close to the coast in



A primary productivity experiment is monitored at sea during the CUEA project.

a narrow bank. Areas of intensive upwelling are located near the heads of underwater canyons and on the sides of capes closest to the equator.

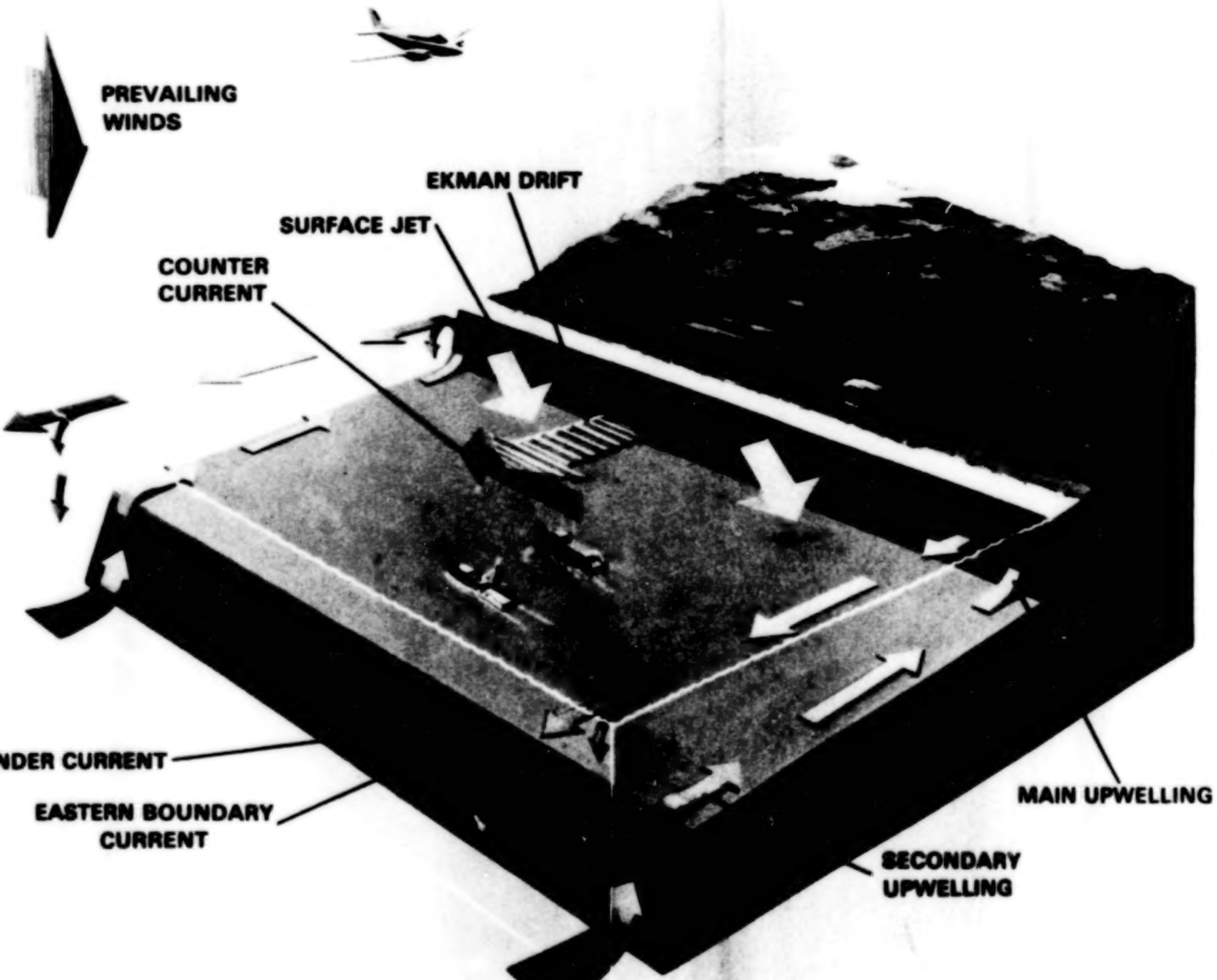
Among upwelling regions, there are distinctly different current patterns alongshore (parallel to the shore) and onshore/offshore (perpendicular to the shore). These structural differences determine the nutrient, oxygen, and regeneration characteristics of the various ecosystems.

Propagation or dispersal of current fluctuations in upwelling regions has been observed alongshore over a distance of 700 kilometers. The fluctuations influence upwelling some distance away from an area affected by local wind forcing. These large wavelike disturbances of the coastal currents affect the productivity of an entire upwelling ecosystem, overriding the effects of local winds and topography.

An undercurrent flowing toward a pole and against the surface flow has generally been suspected in most coastal upwelling regions. CUEA experiments delineated this poleward flow and measured its variations for the first time. Fluctuations in the depth and strength of the undercurrent determine whether vertically migrating organisms—such as dinoflagellates, anchovies, and photosynthetic protozoa—remain in the coastal ecosystem or are removed. Without these underlying countercurrents, the organisms would be swept away by strong surface currents.

The 1976 Peruvian field studies proved that large-scale, remotely driven variations in currents can override effects of local winds and cause a complete change in the biological character of the system. This vulnerability to remote forcing seems to be a function of distance from the equator. The El Niño phenomenon, caused by processes in the western Pacific, disrupts upwelling, reduces productivity, and causes catastrophic declines in fish catches. Understanding and predicting the natural variability in coastal upwelling will require work on ocean processes derived at or near the equator, as will the coupling of equatorial dynamics to coastal processes. (The relation of equatorial processes to El Niño was worked out by physical oceanographers on the NORPAX project, discussed elsewhere in this report.)

CUEA and NORPAX researchers together resolved the interaction of very large scale ocean processes controlling an



Model depicts upwelling processes. The unraveling of the system that brings nutrient-rich water to the surface helped explain a productive anchovy fishery and its fluctuations.

entire upwelling ecosystem. Within the ecosystem, processes affecting phytoplankton involve relatively small-scale phenomena on the order of 5 to 10 kilometers in diameter. CUEA studies did not clearly resolve the effect on coastal ecosystems of mid-scale frontal or plume phenomena 10 to 100 kilometers in diameter. Scientists hope to resolve this complex question in the future.

CUEA studies did define the large- and small-scale phenomena that are vital to upwelling ecosystems; this understanding may be the project's most valuable contribution.

3. Environmental Forecasting

Summary

The Environmental Forecasting Program supported several projects to improve our ability to predict large-scale weather or climate changes. The interaction of oceans and atmosphere are so closely linked that predicting climate changes requires in-depth knowledge about the dynamic processes affecting the mixing and circulation of heat and other ocean properties.

In a dramatic finding, IDOE*-supported investigations showed that the ocean circulation is far more dynamic or energetic than previously thought. Instead of major currents flowing in uniform directions, researchers found swirling bodies of water that included large lenses 1,000 to 1,500 kilometers across; mesoscale or mid-sized Gulf Stream rings 100 to 200 kilometers across; and eddies less than 100 kilometers in diameter. These major features are composed of different water masses with various temperature and salinity characteristics; they may persist for years, carrying heat and salt as part of the global heat transport system.*

The swirling water mass features are now reasonably well understood in the northern Atlantic, where they were studied by the MODE *and* POLYMODE *projects, and in the Pacific, where* NORPAX *scientists investigated them. But the features remain more of a mystery in the Antarctic, where they have been observed as part of the Antarctic Current System. However, results of these studies indicate that heat and other properties carried by the major features in the Pacific help determine large-scale weather patterns over North America. The importance of the smaller ocean features in affecting climate is a subject for continuing research.*

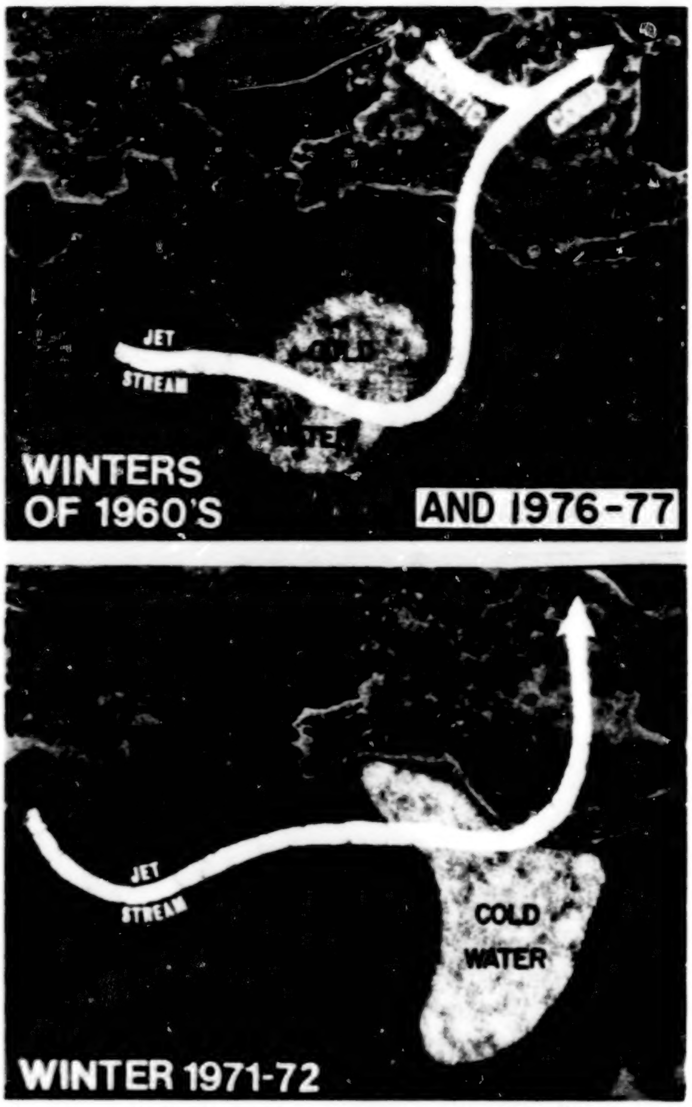
IDOE *findings about ocean eddies led oceanographers all over the world to become increasingly involved in eddy research. Work in the tropical Pacific led to an explanation of a periodic infusion of warm ocean water off the coast of Peru. Called El Niño, this phenomenon severely affects the local fishing industry when it occurs. An* IDOE *meteorologist made the first scientific forecast of an El Niño in 1974; future forecasts will enable positive steps to minimize the effects of this natural event.*

On a longer time scale, IDOE *studies of the ice age showed how the ocean looked during times when glaciers covered large parts of continents in the Northern Hemisphere, as they have done repeatedly in the past few million years. These studies demonstrated that changes in the earth's relationship to the sun control advances and retreats of continental ice sheets. Information useful for predicting future ice ages was obtained; since the earth is now warmer than in most of the recent past, such information can also help predict probable climate conditions.*

The North Pacific Experiment (NORPAX)

NORPAX grew out of early studies on air-sea interactions in the Pacific by meteorologists Jacob Bjerknes and Jerome Namias of the Scripps Institution of Oceanography in California. After studying 30 years of sea-surface temperature data, Namias suggested that enormous patches (up to 2,000 kilometers across) of surface water in the North Pacific are unusually warmer or cooler than surrounding waters. The patches seem to last several years—long enough to interact with the overlying atmosphere, which in turn could affect weather and climate in North America. Critics of this hypothesis argued that the temperature variations or anomalies identified by Namias might have been caused by the ships from which the temperature measurements were made—for instance, by heat from their engines. Since there were no data to refute this argument, the question was unresolved.

NORPAX provided the data needed to examine how the North Pacific Ocean receives, stores, transports, and releases heat. The experiment aimed to determine how the large (50- to 2,000-kilometer) surface thermal features evolve and persist for periods of weeks to years, and how much the ocean surface affects the overlying atmosphere. In the first few years, work focused on temperate latitudes, because of their direct connection with weather in the continental United States.



Weather on the North American continent is affected by shifts in the jet stream in relation to areas of cold and warm surface waters in the Pacific. NORPAX *investigators discovered that when a pool of warm water lies near the west coast of the United States and is accompanied by a pool of cold water in mid-ocean, the jet stream follows the path shown here. Moisture is picked up and transported inland, where extra precipitation falls over the North American continent.*

Tracking Temperature Changes

The **NORPAX** Anomaly Dynamics Group studied sea-water properties and monitored the apparent temperature anomalies charted by Jerome Namias. Water temperatures at various depths were taken by commercial ships and aircraft using expendable bathythermographs (**XBT**s)—instruments that allow temperatures to be plotted against depth without requiring a ship to stop or slow down. These measurements, referred to as Trans-Pacific or **TRANSPAC** bathythermograph sections, showed that some surface waters in mid-latitudes store vast quantities of heat.

TRANSPAC broadened the scope of **NORPAX** to include the tropical latitudes of the North Pacific, providing 500 temperature profiles each month for five years. These data confirmed Namias's work, showing that typical lenses of unusually warm or cold waters are roughly 1,500 kilometers in diameter and range from 1 to 1.5 degrees above or below the average ocean conditions. The surface anomalies often extend to depths of 200 to 300 meters and may last well over two years.

The causes of these anomalies vary with location and season. Direct air-sea surface exchange, vertical circulation, wind mixing, and advection all play important roles. The evolution of these warm and cold waters has been successfully charted using numerical models that account for all these processes, along with wind and heat flux. However, it is not yet possible to predict when and where an anomaly will evolve. Other government agencies have proposed to continue and possibly expand the **XBT** program, since **NORPAX** field work ended in 1980.

A second **NORPAX** field program used satellite-tracked drifting buoys set at 30 meters below the surface. Some 100 of these drifters were released at temperate and tropical latitudes, then tracked by satellites as they dispersed over several months. Drifter trajectories revealed remarkably simple patterns. During moderate and high winds, the upper waters seemed to be driven predominantly about 30 degrees to the right of the mean wind direction, at speeds proportional to wind velocity. At tropical latitudes, trajectories indicate cross-equator flows and extensive north-south heat transport.

The influence on the atmosphere of sea-surface temperature anomalies in temperate latitudes remains obscure from **NORPAX** results. For example, long time-series records of sea-surface temperature and overlying atmospheric conditions show only a very weak linear relationship between the two. However, somewhat more subjective (and nonlinear) forecasts of extreme events, such as the unusually cold winter of 1976-77, seem to show a stronger correlation. It will take a longer time-series of forecasts matched against observations to assess the impact of ocean-surface conditions on climate variations.

Numerical models augmented still inadequate observations of the ocean interacting with the atmosphere. Responses of models to simulated sea-surface temperature conditions show that the influence on the atmosphere of sea-surface temperature changes in the tropical Pacific is easier to see than that of similar anomalies in temperate latitudes. In the latter area there may well be a response, but it is obscured by natural variability.

Predicting El Niño

Successful modeling results for ocean conditions along the Peruvian coast, together with a long-standing interest in the dramatic—often drastic—fluctuation in the fisheries resources there, encouraged **NORPAX** oceanographers to focus attention on the tropical Pacific. As described before, El Niño is a periodic event off the Peruvian coast, in which rich fishing grounds turn barren in response to subtle changes in the ocean far removed from the area. Since the event usually occurs around Christmas time, Peruvians have named it El Niño, "The Child."

An extensive network of Pacific Island tide gauges measured subtle changes in sea level. During the 1972 El Niño, the sea level rose in the eastern islands and declined in the western ones. This observation led NORPAX oceanographer Klaus Wyrtki, from the University of Hawaii, to formulate the currently accepted picture of El Niño as a rocking of the tropical ocean across the entire basin, caused by changes in the trade winds thousands of kilometers from Peru and up to a year beforehand.

According to Wyrtki's theory, stronger-than-normal trade winds pile up warm water in the western tropical Pacific. These winds are followed by a period in which the trades diminish from a large area of both the central and western tropical Pacific. Unsupported by wind forces, the warm water piled up to the west moves rapidly eastward like a wave and washes up along the coast of South America. This warm water, low in nutrients and salinity, apparently creates a thin, low-density surface layer that keeps the deep water (colder, denser, and nutrient-rich) from welling up to the surface.

An abrupt decline in productivity is one of the most important effects of this wave on the normally rich fishing area off Peru. During the 1960s, the youthful Peruvian fishing industry accounted for the greatest tonnage of fish protein landed among all the nations of the world, exceeding Japan, the USSR, and China. After the 1972 El Niño, however, the Peruvian catch fell to about 20 percent of its earlier levels. This precipitous drop not only had a disastrous effect on the economy of Peru, but it disrupted world commodity markets as well. The Peruvian anchovetta fishery has yet to recover.

In 1974, NORPAX meteorologist William Quinn made the first scientific forecast of an El Niño (the one in early 1975), using the atmospheric pressure gradient between the Indonesian equatorial low and the South Pacific subtropical high. Anomalies in this pressure gradient were correlated with the trade wind deviations that set up the rocking of the tropical ocean.

After Quinn's forecast of the small 1975 El Niño, NORPAX oceanographers mounted the "El Niño Watch" Expedition, the first attempt to observe and follow one of these phenomena from its onset. After this effort, NORPAX oceanographers and meteorologists planned for a larger field experiment to coincide with, and use the data from, another international project. This was the independently sponsored Global Weather Experiment, between Hawaii and Tahiti. This later IDOE work was designed to show how the NORPAX island-tide gauge and the tropical XBT network of commercial ships could be used to monitor equatorial currents over an extended period of time. As in other areas of climate research, this long-term approach seemed the best way to observe and study infrequent, extreme events like El Niño. Results of this effort are still being analyzed.

MODE and POLYMODE

In the mid-1950s, the Swallow float revolutionized understanding of deep-sea currents. This float hovers at or near a prescribed depth and is carried horizontally by subsurface currents. It emits a sound signal that can be tracked by a surface vessel. The first Swallow float experiment revealed energetic motions a few hundred kilometers in size at a deep-water site near Bermuda. These motions, which swirled like atmospheric storms, became known as mesoscale eddies. Similar eddies were soon described in many ocean areas.

Early measurements of the size and strength of typical mesoscale eddies, plus some general idea of their distribution, suggested that they account for more than 90 percent of the kinetic energy in the ocean. (Previously most of that energy was thought to be in the major currents.) This revolutionary discovery, plus the implications for heat and momentum flux within the large-scale general circulation patterns of the ocean, so impressed physical oceanographers from many countries that eddy research grew substantially during the 1970s.

Intensive field work on eddies began in 1970 with the Soviet POLYGON experiment (named for the arrangement of the mooring instruments deployed). It was followed by the Mid-Ocean Dynamics Experiment (MODE-O) from 1971 to 1973, the intensive U.S.-U.K. MODE-1 experiment in 1973, the U.S. MODE-1 Extension through May 1975, and finally POLYMODE, a joint U.S.-USSR experiment in the

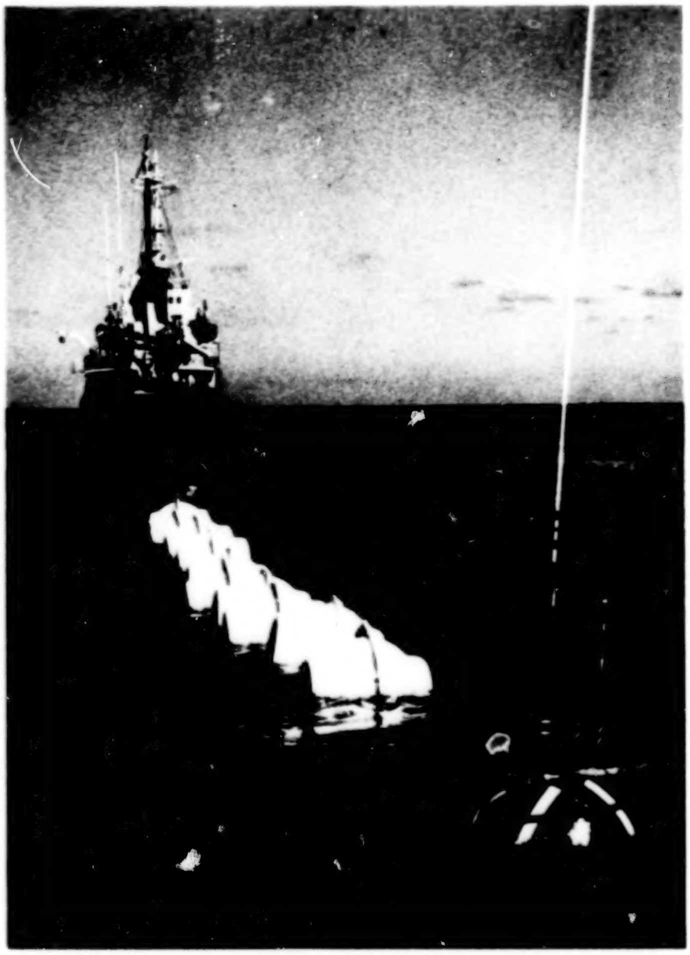


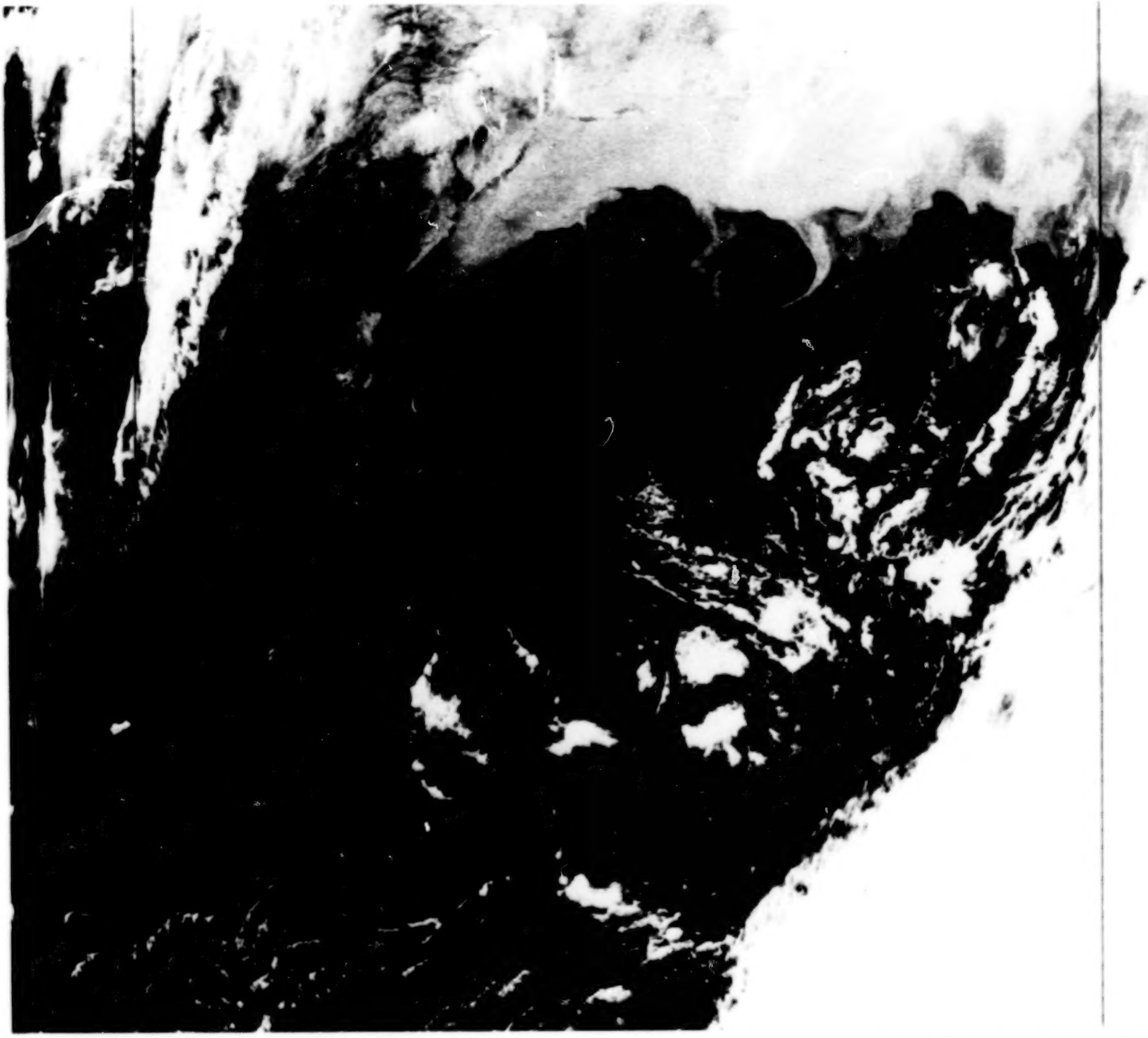
Figure shows launch of a subsurface mooring during MODE-1 project. The radio float in foreground is the topmost mooring component. Flotation units behind the float keep it upright. The ship lays the entire length of mooring along the surface, then the anchor is attached and dropped, pulling the mooring underwater. The radio float rests some 500 meters below the surface and records data on current direction and intensity. For recovery, a radio-activated release drops the anchor and flotation brings the mooring to the surface. Collected data are then retrieved.

western North Atlantic. Complementing POLYMODE were Canadian measurements south of Newfoundland, as well as French, German, and British work in the eastern North Atlantic called NEADS (North East Atlantic Dynamics Study). These studies found eddies throughout the eastern North Atlantic.

MODE research focused attention on a 300-kilometer-square area of the North Atlantic southwest of Bermuda. This locale was doubled in size by intensive POLYMODE studies, which also focused on the mid-Atlantic and other areas to understand better the energy field or forces causing circulation and eddies across the entire Atlantic.

By the end of MODE-1, the study of Atlantic eddies had broadened to include Gulf Stream rings, intensely rotating bodies of water several hundred kilometers in diameter, which pinch off from large meanders or variations in the Gulf Stream flow. These rings are similar in depth (500 meters) and move at a speed like that of the Gulf Stream itself. In the eastern North Atlantic, rings from the Gulf Stream extension can be up to 1,000 kilometers in diameter but move more slowly. Rings differ from mesoscale eddies: their innermost water comes from the onshore side of the current that formed them. Thus Gulf Stream rings enclose cold slope water in their interiors and can always be identified by their distinctive water mass properties. MODE eddies, on the other hand, encircle ambient mid-ocean water with much weaker currents.

POLYMODE researchers discovered several new types of mesoscale features. The most energetic was a wavelike water jet. It appears to be a seasonal event transporting a very large amount of water and energy as part of the recirculation of the Gulf Stream. The wavelength of the jet was 400



Gulf Stream rings are clearly visible from this satellite photo. White masses are clouds and the warmest water shows as the darkest. Gradations show from light continental shelf water to darker slope water to yet darker waters of the Gulf Stream. Warm Gulf Stream water has been entrained by the strong circular flow of these rings, which move away from the Gulf Stream and circulate about the North Atlantic, persisting for up to two years.

kilometers; its crests move from west-southwest to east-northeast, toward the Gulf Stream, and last a few months. Unlike waves driven by surface winds, energy in these large-scale ocean waves need not be carried in the same direction that the crests travel. Thus one plausible interpretation is that the waves originate in the vicinity of the Gulf Stream and radiate energy outward.

Perhaps the most surprising eddies found by POLYMODE investigators were relatively small (25 to 30 kilometers in diameter), highly energetic, spinning parcels of different water masses, only a few hundred meters thick. Three such eddies were observed in the area of the Gulf Stream. One small eddy, discovered at a moderate depth, carried water from north of the Gulf Stream and may have been spawned from a Gulf Stream ring. Another eddy at a lesser depth consisted of water from the tropical Atlantic. This eddy entrained and held a sound-fixing and ranging (SOFAR) float—the modern equivalent of a Swallow float—for some 20 revolutions over a two-month period. These two features, carrying water types from opposite sides of the Atlantic, were at one point aligned directly over each other. Yet another small-scale eddy found off the Antilles Islands contained Mediterranean waters and was thereby christened "meddy."

Current-meters were deployed to span the Mid-Atlantic Ridge east of Bermuda and in the North Equatorial Current. The goal here was more understanding of the dynamics of the Atlantic both east and west of this major geographic feature. Data from these meters were also sought to help scientists apply MODE and POLYMODE findings to the circulation of the entire ocean. Eddy energies across the Mid-Atlantic Ridge were similar to those in the Gulf Stream region. However, near the ridge, energies in the deep waters were greatly diminished, suggesting that the mountainous bottom topography of the ridge absorbs these energies. Just how this happens is a subject for future inquiry.

The Mid-Atlantic current-meters also made an unusual finding about the mean flow of near-surface waters. One pair of current-meters at a southern site, 100 kilometers apart, recorded mean flows in opposite directions for over a year. A second mooring pair spanning the edge of the Mediterranean salt tongue recorded similar data. This suggests a long-term, stable, mid-ocean front or energy gradient. There was also no evidence of deep currents along the eastern rise off the Mid-Atlantic Ridge. Detailed results from the European NEADS experiment in the eastern basin, which should clarify energy fields there, are not yet compiled at this writing; however, energy levels and earlier measurements suggest the presence of Gulf Stream extension rings and eddies like those found in the MODE area.

Ongoing research aims to identify better the energy source of open-ocean eddies. Neither direct wind forcing nor the instability of mid-ocean currents appears to be the sole source. Instability of the Gulf Stream is a leading candidate and is unquestionably the source of ring energy. But numerical models and observations suggest that energy transfer processes in the Gulf Stream and its surrounding waters are extremely complex.

POLYMODE researchers suggested that the ultimate source of the energy driving open-ocean eddies is the Gulf Stream and its recirculation gyre or spiral, through a very complex series of ocean and atmospheric interactions. Scientists understand the importance of this energy in driving ocean currents and affecting weather on the continents; however, the details of processes involved and their role in affecting climate is a subject for continuing study.

Models: A Key Tool

Computer modeling of ocean circulation has been central to eddy studies and progressed enormously during the 1970s. Current eddy models can reproduce the essential features of real ocean flows quantitatively for most time periods. Researchers are now working to increase confidence in their models, to compare various kinds, and to determine the regional and oceanic role that eddies play in circulation mechanics. Calculations from one model, for example, suggest that in the immediate vicinity of the Gulf Stream, eddies do all the work in carrying heat from the North Atlantic basin toward the North Pole. Such model results will be used during the interpretive phases of POLYMODE and will be a basis for the oceanic components of combined air-sea models in future climate research. Better understanding of these phenomena will lead to more knowledge on how the ocean influences weather and climate.

International Southern Ocean Studies (ISOS)

The three ocean basins (Atlantic, Pacific, and Indian) are connected through the little-known Southern Ocean. Several unique features of this ocean make it especially interesting

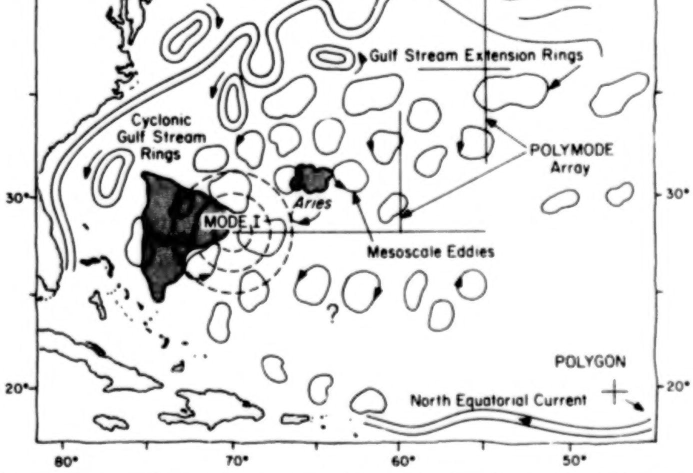


Chart shows locations of some areas and major current features studied under the MODE *and* POLYMODE *projects.*

to physical oceanographers. Strong, diverging wind—along with sharp temperature and salinity gradients in surface waters around Antarctica—help set up a complex north-south circulation of water that carries quantities of heat, salt, and nutrients from northern deep waters into the Southern Ocean. This water upwells to the surface, cools, and forms yet colder, dense Antarctic water; it later sinks beneath the less dense mid- and surface waters and spreads northward into all three basins along the deep-ocean bottom. Exchanges of heat, salt, and momentum and the transfer of properties between water masses and the air in this region are as vigorous as they are poorly understood. Yet through these waters, the deepest part of the ocean interacts directly with the atmosphere.

ISOS was a project to improve our understanding of the Antarctic Circumpolar Current. It was set up to (1) identify how much the current varied in time and space in selected regions; (2) develop and test theories of dynamic balance; (3) identify the Southern Ocean's role in global climate dynamics; (4) promote understanding of Polar Frontal Zone dynamics and their relationship to the Circumpolar Current; and (5) improve our understanding of water mass formation, mixing, and exchanges with other oceans.

The U.S. component of ISOS involved investigators from six universities, the Pacific Marine Environmental Laboratories of the National Oceanic and Atmospheric Administration (NOAA), and the Woods Hole Oceanographic Institution in Massachusetts. After it began in 1973, the program grew into a truly international endeavor, with scientists from 12 countries cooperating.

ISOS field experiments have included long-term monitoring of the Antarctic Circumpolar Current in the Drake Passage region; studies of the Polar Frontal Zone and of water mass renewal and circulation in the Subantarctic Zone; and measurements of winter oceanographic conditions beneath sea ice. There have also been analyses of historical and laboratory data and numerical modeling studies.

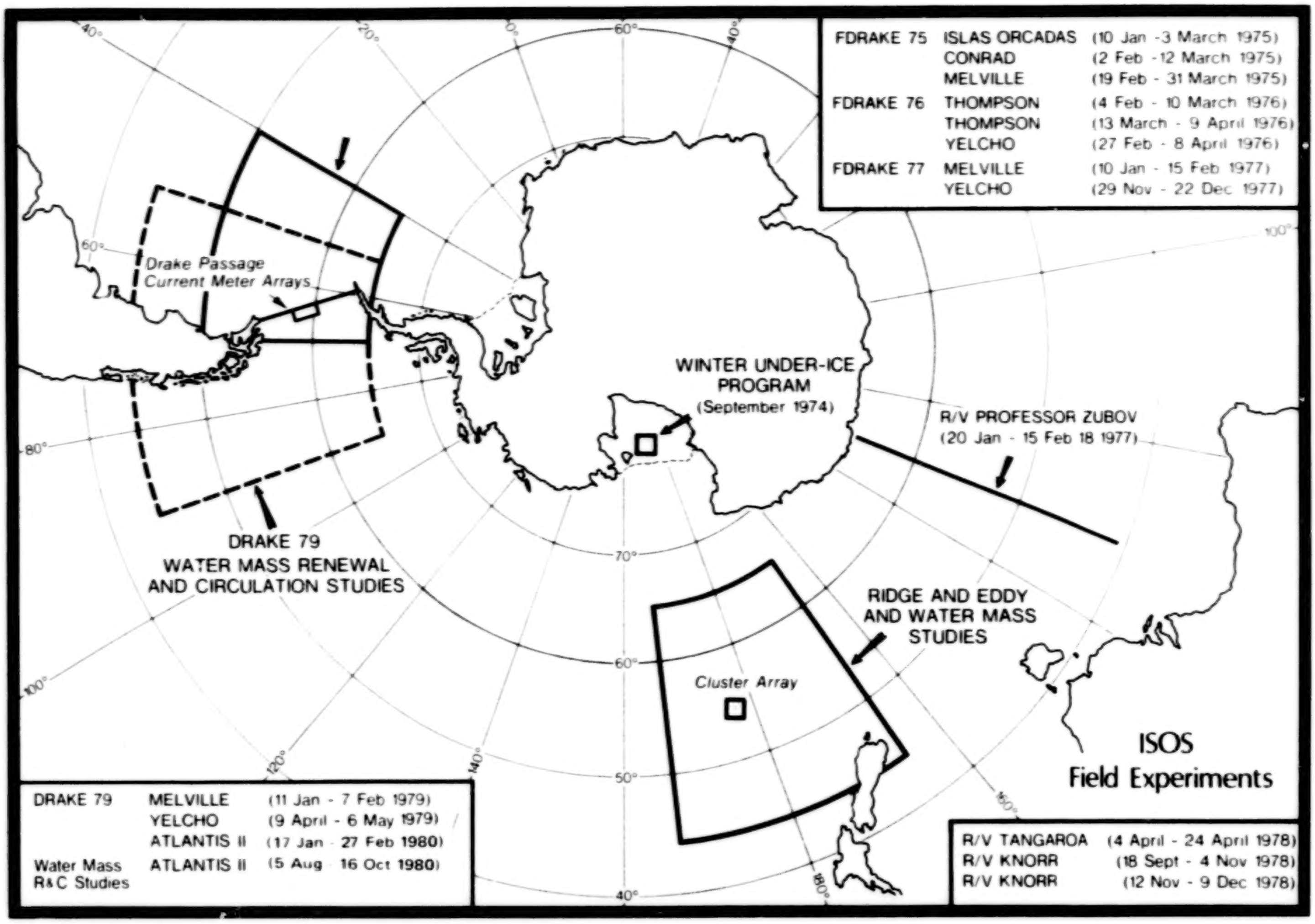
The Drake Passage is a constriction between South America and Antarctica. Through it the Antarctic Circumpolar Current must flow, much like the Florida Straits and the Gulf Stream system. The current is narrowest there, and the region is fairly accessible for current-meter studies. Current-meter arrays were set across the passage to record water transport continuously through the year. Using these data and extensive hydrographic survey work, researchers are now certain that the mean Antarctic Circumpolar Transport during the 1970s was some 120 million cubic meters per second to the east.

Researchers also revealed that the Antarctic Circumpolar Current does not have a single coherent flow, as previously thought. Instead it has three distinct and narrow (100-kilometer) jets flowing in the boundary-gradient zones between four distinct, now well-defined, water-mass types in the Drake Passage and the western Scotia Sea. Narrow currents of high velocity exist between (1) subantarctic surface water and the northern extent of the transition Polar Frontal Zone; (2) the southern boundary of the Polar Frontal Zone and the Antarctic surface water; and (3) the Antarctic surface water and the continental water. Strong currents extend to the bottom except near large topographical features.

Heavily clad scientists handle an ISOS mooring in Drake Passage. (Photo by Doug Brunell)

Individual current jets seem to share many of the characteristics of western ocean boundary currents. For example, they meander as much as 100 kilometers within a few weeks. A long meander in the central jet, which is identified with the traditional Antarctic Circumpolar Current, was seen to form a closed ring, roughly 100 kilometers in diameter and similar to those identified in the MODE experiment area, described above. This ring pinched off and drifted away from the main current into the quiescent zone to the north. Current-meters in these zones recorded energetic and anomalous temperature events of short duration.

As in most other regions of strong currents in the ocean, there is an active mesoscale eddy field, probably driven by the currents themselves. Estimates of global north-south heat transport based on assumptions about the global distribution of eddies (measurements were confined to the Drake Passage, which may not be typical of the open-ocean Antarctic Circumpolar Current System) can account easily for most of the poleward heat flux required for climatic stability. This is a tremendously important discovery, since heat transport toward the Pole cannot be affected by the


FDRAKE 75 ISLAS ORCADAS (10 Jan -3 March 1975)
CONRAD (2 Feb - 12 March 1975)
MELVILLE (19 Feb - 31 March 1975)
FDRAKE 76 THOMPSON (4 Feb - 10 March 1976)
THOMPSON (13 March - 9 April 1976)
YELCHO (27 Feb - 8 April 1976)
FDRAKE 77 MELVILLE (10 Jan - 15 Feb 1977)
YELCHO (29 Nov - 22 Dec 1977)
Drake Passage Current Meter Arrays
WINTER UNDER-ICE PROGRAM (September 1974)
R/V PROFESSOR ZUBOV (20 Jan - 15 Feb 18 1977)
DRAKE 79 WATER MASS RENEWAL AND CIRCULATION STUDIES
RIDGE AND EDDY AND WATER MASS STUDIES
Cluster Array
ISOS Field Experiments
DRAKE 79 MELVILLE (11 Jan - 7 Feb 1979)
YELCHO (9 April - 6 May 1979)
ATLANTIS II (17 Jan - 27 Feb 1980)
Water Mass R&C Studies ATLANTIS II (5 Aug - 16 Oct 1980)
R/V TANGAROA (4 April - 24 April 1978)
R/V KNORR (18 Sept - 4 Nov 1978)
R/V KNORR (12 Nov - 9 Dec 1978)
40°
20°
0°
60°
40°
60°
80°
100°
100°
70°
60°
50°
40°
120°
140°
160°
180°

easterly flowing Antarctic Circumpolar Current System itself. It must arise entirely from cross-stream processes.

Although eddies carry heat toward the poles, they seem to transport salt toward the equator. However, the high-latitude salt balance requires a poleward transport, since precipitation there exceeds evaporation. A mechanism that can transport both salt and heat poleward has been found in small-scale (100 meters vertically, tens of kilometers horizontally) intrusions of water across the Polar Front Zone.

Shallower water masses north of the Polar Frontal Zone seem to form in limited regions containing increasingly colder water as one travels east from South America. The Drake Passage itself serves as the barrier for the temperature variation, with coldest water just west of the passage. How these water masses distribute themselves into zones and sink as they progress toward the equator is a topic of ongoing study.

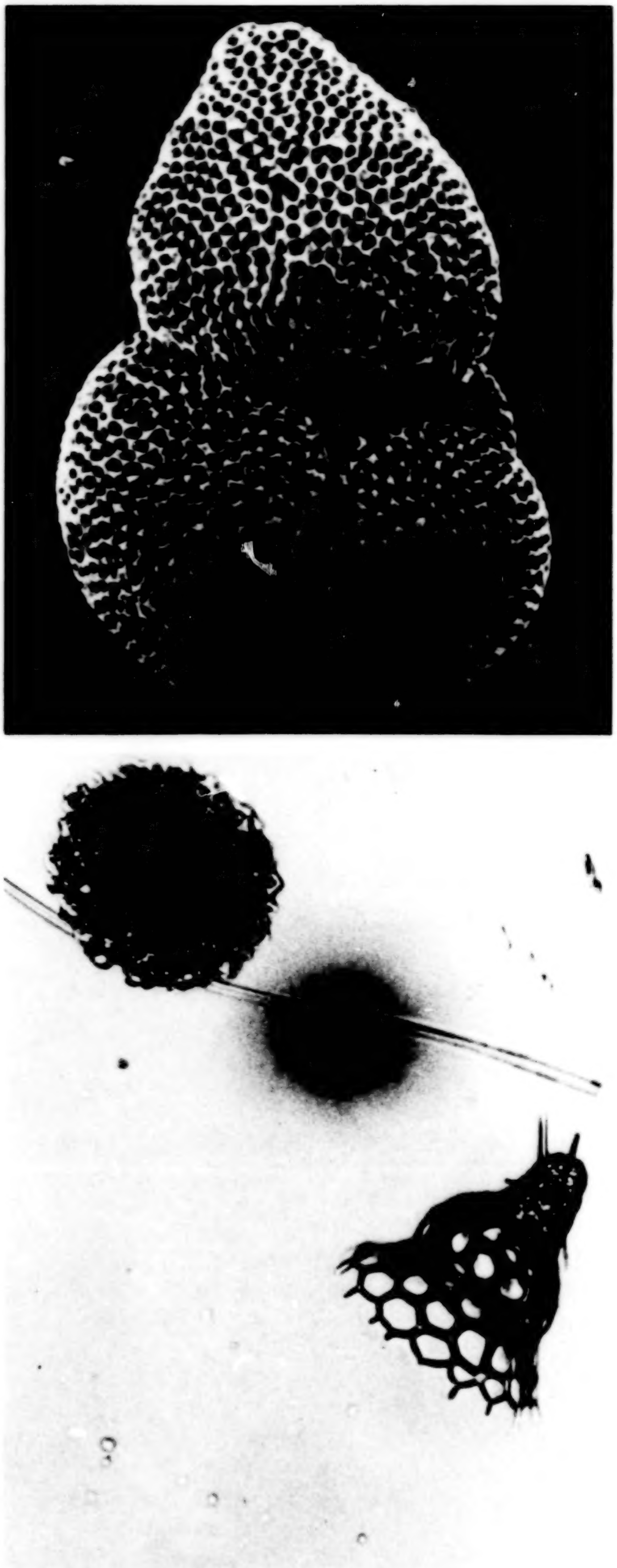
Climate: Long-Range Investigation, Mapping, and Prediction (CLIMAP)

CLIMAP investigators studied major changes in the earth's climate over the past million years. Their major aim was to understand transitions between the two stable states of global climate, or ice ages, and temperate interglacial periods. The intent was to provide a basis for predicting future climate change.

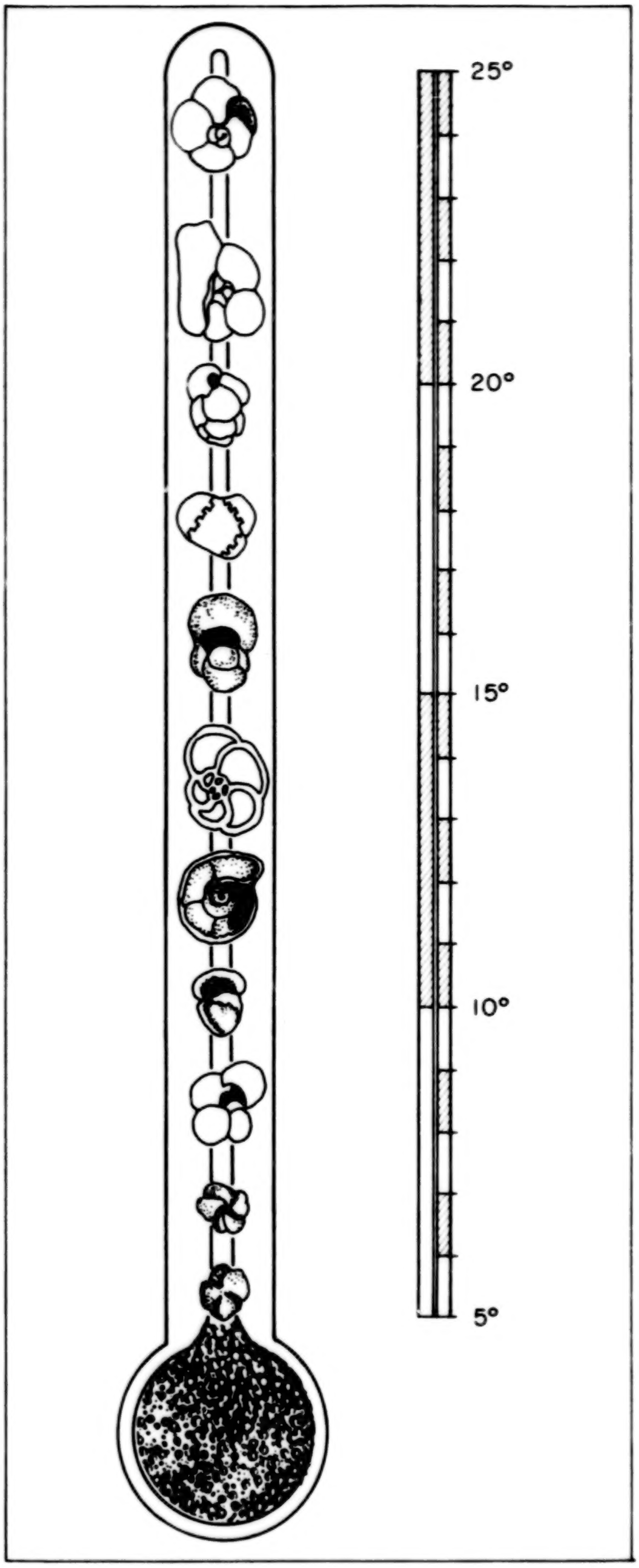
Analysis of planktonic fossils preserved in ocean sediments gave information about changes in climate, ocean circulation, sea-surface temperature, and climatic change. The types and abundance of microscopic plants and animals were identified from their fossilized remains, taken from cross-sections of deep-sea sediments. Since the sediments from which the fossils were taken could be dated, inferences about the temperature and salinity conditions of ancient oceans could be inferred, based on the assumption that the environmental requirements of modern planktonic plants and animals are the same as they were for their ancient ancestors.

CLIMAP researchers analyzed nearly 500 ocean sediment cores collected over the past 30 years. Distributions of fossil plants (coccoliiths, diatoms) and animals (foraminifera and radiolaria), as well as the composition of their remains and rates of sediment accumulations, were compared with present distributions. Using this approach, CLIMAP scientists were able to map the temperature distributions of surface water for a typical February and August 18,000 years ago. And they estimated ocean currents for those times.

Global sea-level changes, caused by the freezing and transfer



Globigerinoides sacculifer *(top) and* Cycladophera davisiana *(bottom) are microfossils that provided water temperature indicators for* CLIMAP *investigators. The preferred habitats of these two are, respectively, tropical and Antarctic. (Photo at left by Allan W. H. Bé)*



This paleothermometer shows how fossil sediments are used to estimate sea-surface temperature. Microorganisms, such as the species of foraminifera drawn here, live near the ocean surface. Once they die, their remains sink, accumulate, and fossilize in ocean sediments. When numbers of a particular species are found in a sediment layer, this indicates a certain surface water temperature at the time that sediment layer was deposited.

of water from oceans to ice caps, were calculated by determining ice volume. Maximum and minimum ice-sheet coverages indicate sea-level changes on the order of 150 to 100 meters, respectively. Some ocean regions, such as central water masses, changed little. Other areas, especially the subtropical and subpolar oceans, showed considerable change.

Huge continental ice sheets (up to 3 kilometers thick), pack ice, and marine-based ice sheets once covered large parts of the Northern Hemisphere. Sea ice in the Southern Hemisphere also covered a larger area than now. An increase in the global surface albedo, or reflectance, of incoming solar radiation resulted from expanding areas of permanent ice and changes in land vegetation as grasslands and deserts spread and forests diminished. These changes led to a general cooling of the earth's surface. The mean air-temperature decrease during the ice age was only 5 degrees Celsius and about 2.5 degrees Celsius on the ocean surface.

Ice-age ocean temperature charts were compared to maps of ice sheets and other data for the last period of maximum glacial conditions. Results then allowed researchers to make deductions about the ice-age atmosphere. Climate variations were primarily attributed to changes in the volume of glacial ice in response to changes in ocean surface waters.

CLIMAP research also verified for the first time the Milankovich theory that changes in the earth's orbit around the sun are a major cause of ice ages. This theory holds that ice ages are caused by changes in seasonal and latitudinal distribution of solar energy resulting from changes in the earth's solar orbit. Three periodic variations in the earth's orbit are known from changes in the position of planets in the solar system. These are (1) variations in the eccentricity of the orbit, with an average period of about 100,000 years; (2) variations in the tilt of the earth's axis, with a period of about 41,000 years; and (3) a 22,000-year cycle in the position of the orbital paths at which a given season occurs. According to a modified version of the Milankovich theory, each of these recurrent events should be trackable in fossilized climatic records—if, in fact, the orbital changes are the fundamental cause of the ice ages.

CLIMAP researchers assembled long climatic records from two deep-sea cores in the southern Indian Ocean; they thus confirmed the Milankovich theory. They also discovered climatic recurrences so close to those predicted that orbital changes are now considered the primary cause of the ice-age cycle. CLIMAP provided the first definitive estimate of the largest climatic changes of the past million years; this estimate is a basis for judging the impact of future climate changes.

4. Environmental Quality

Summary

IDOE's Environmental Quality Program was set up to provide data on ocean pollution. Projects ranged from worldwide surveys of the present state of the ocean to detailed studies of the cellular responses of marine organisms to experimentally introduced pollutants.

The Baseline project began by measuring pollutant levels in sediments, organisms, and seawaters, to determine the extent of pollution worldwide. These studies showed that the most troublesome areas are coastal ocean waters, while the open sea remains relatively free of most pollutants, except those carried by the winds. The project recommended more work to come up with ways to detect pollutants at extremely low levels. More sophisticated techniques might reveal problems not yet discovered.

The Geochemical Ocean Sections Study (GEOSECS) determined distributions and interactions of various chemical constituents in the ocean. One of the most striking results concerned tritium, a radionuclide (radioactive isotope) with a 12-year half-life. This isotope, introduced into the environment from atmospheric testing of hydrogen bombs, had penetrated the intermediate depths of the North Atlantic Ocean. As a result of this discovery, much was learned about mixing of gases between the ocean and atmosphere and mixing of waters within the ocean. This information is a basis for learning how the ocean takes up excess carbon dioxide from burning fossil fuels, which in turn is necessary for accurately predicting how the buildup of gases and pollutants in the atmosphere increases earth temperatures.

The Sea-Air Exchange (SEAREX) project studied atmospheric transport of materials to the open ocean. The work has shown that dust from the Sahara Desert can be detected thousands of miles away in the North Atlantic, and dust from Asian deserts is found on Enewetak Atoll, a remote coral island just north of the equator in the Pacific. These dust particles are major contributors to deep-ocean sediments and serve to remove certain pollutants that exist in the atmosphere as gases.

The Pollutant Responses in Marine Animals (PRIMA) project developed techniques to detect and evaluate subtle changes in organisms resulting from exposure to pollutants. Such early warnings will permit corrective actions before irreversible damage occurs either to lone species or entire ecosystems.

A major advance in the experimental techniques available to chemists and biologists came from the Controlled Ecosystem Pollution Experiment (CEPEX). Large plastic bags, called controlled experimental ecosystems, were developed to enclose sizable quantities of water, containing natural populations of plants and animals, and to hold the water for months while pollutants and other materials were introduced. These experiments showed that adult marine animals were less susceptible to pollutants than were juveniles, and that bacteria were relatively resistant to pollution because of their rapid reproduction and many different forms. Community structure—the numbers of one species in relation to another—was also shown to change with increased amounts of pollution. These data reinforced an earlier conclusion that the oceans are not dead but have a remarkable capacity to recover from local disturbances.

Baseline Studies

The Baseline project was one of the first supported by the Environmental Quality Program. Its researchers sought to determine the health of the oceans by assessing pollutants in sediments, marine organisms, and ocean waters. Studies took place on both the coasts and open seas of the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Caribbean Sea. Results indicated that most pollutants were restricted to coastal ocean waters and estuaries. The open ocean was relatively free of most pollutants, although some were carried there by the atmosphere.

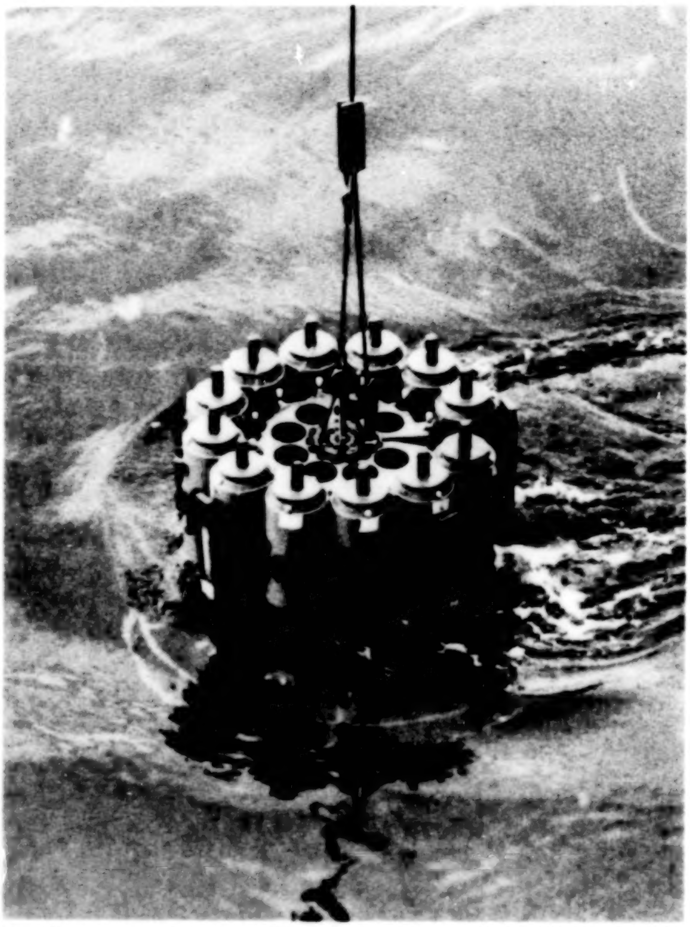
Three activities that started with the Baseline project continued through the Decade. First was the extra attention paid to improving seawater collection and handling techniques to eliminate contamination of samples prior to analysis. Second was work to design and improve analytical techniques themselves, to provide reliable data on the extremely low levels of many ocean pollutants. Finally, Baseline projects gave direction for later studies on ocean pollution.

The project did provide some benchmark data for future ocean pollution studies. But perhaps the most valuable contribution was a set of recommendations, published in 1972, that formed the underpinnings for further detailed Environmental Quality programs.

Geochemical Ocean Sections Study (GEOSECS)

GEOSECS scientists sought to focus on the interaction of chemical and physical processes that control the way chemical elements and other constituents are distributed in ocean waters. Although the project was basically chemical in nature, physical oceanography played a major role, since the study involved little-known deep-ocean currents and their rates of circulation. Like many IDOE programs, GEOSECS has provided extremely useful answers to some key questions and concerns. One is the disposal of wastes in the open sea; another is the ocean's role in moderating possible climate changes that arise from excess carbon dioxide released into the atmosphere from burning coal and oil. GEOSECS data will be available in a set of atlases for other scientists to use.

A computer aboard the R/V Knorr *displays data collected by instruments in the water.*



The Rosette Sampler was a principal GEOSECS *research tool. It continuously monitors water conditions as it is lowered from the surface and relays this information to a ship's computer. Water samples may be collected at any depth at a scientist's command. (Photo by Alan Fleer)*

Sophisticated water sampling systems were devised to permit oceanographers to measure water temperature, salinity, and other significant features while simultaneously sampling specific water masses (bodies of water having unique temperature and salinity characteristics). Though most information was processed at sea, an operations group onshore, at the Scripps Institution of Oceanography, completed some analyses and compiled the data.

Twenty-one institutions were involved in the GEOSECS program, 14 in the United States and others in Belgium, Canada, France, Germany, India, Italy, and Japan. The U.S. shipboard program consisted of three expeditions on vessels run by the Woods Hole Oceanographic Institution (R/V *Knorr*) and the Scripps Institution of Oceanography (R/V *Melville*). Atlantic field work aboard the *Knorr* took place from July 1972 to April 1973. The ship occupied 116 stations from 75 degrees north latitude in the Greenland Sea to 61 degrees south latitude in the Drake Passage. More than 10,000 water samples, ranging in size from small glass ampules to 100-liter plastic drums, were collected.

At the end of the *Knorr* cruise, deck gear and analytical equipment were transferred to Scripps for the *Melville's* 10-month (1973-74) Pacific expedition, which included 147 sampling stations. During the next 3 1/2 years, GEOSECS scientists concentrated on the analysis of Atlantic and Pacific samples. The final phase of field work was a 5-month Indian Ocean voyage by the *Melville* in 1977-78.

The most dramatic GEOSECS advances came in physical oceanography. Careful measurements of tritium, a radionuclide produced by hydrogen bomb testing in the atmosphere, enabled scientists to track the formation of intermediate waters (1 to 4 kilometers deep) in the North Atlantic south of Greenland. Since the atmosphere is the sole source of tritium in the ocean, and since the age of the tritium could be determined from its half-life, researchers were able to trace a particular water mass, labeled intermediate water. Formation of this water mass at the sea surface (where the tritium was introduced) and its later sinking and mixing are so rapid that they can be followed, using the short-lived radionuclide. By analyzing the ratio of tritium to its decomposition products, the age of the tritium—and hence the age of the water mass from which it was collected—could be determined.

This work showed that deep Atlantic Ocean water is renewed every 100 to 150 years instead of every 600 to 750 years, as previously believed. Most deep-ocean processes are much slower and need hundreds or thousands of years to complete. These processes require measurements of some of the radionuclides that occur naturally, such as radium and its second-generation products.

Chemical aspects of biological activity were also studied by GEOSECS scientists, who measured various nutrient levels. These studies determined the rates at which nutrients are removed from productive, sunlit surface waters by the sinking of dead plants and animals. This organic material sinks into the deep waters, where its nutrients may be recycled through the process of upwelling. This recycling was studied by scientists in the CUEA project, described elsewhere in this report.

This same organic material, along with fecal pellets, was discovered to carry metals and other chemicals to the ocean bottom. As the material sinks from surface waters and decays, the bound metals are chemically released. This is now known to be a prime mechanism controlling metal concentrations in the deep ocean. Rapid settling of large particles formed by zooplankton (e.g., fecal pellets) is the main way materials, including some that are radioactive, are removed from surface layers and carried to the sediments. Knowing about these processes helps scientists predict the fate of radioactive fallout from nuclear weapons detonated in the atmosphere. And such knowledge is needed to plan or regulate waste disposal in the ocean.

GEOSECS data also revealed how ocean-bottom processes affect the chemical composition of dissolved gases in the ocean. Unexpected discoveries of dissolved helium-3 in deep-ocean waters showed that the earth's interior is still losing primordial gases incorporated at the time of its formation. These gases, removed from the deep mantle perhaps 100 kilometers below the ocean floor, are ejected into the ocean by hydrothermal vents on the mid-ocean ridges, where new oceanic crust forms. Using these distinctive signals, the active outgasing of the earth's interior, geologists and geochemists can pick promising areas to study the role of crust formation in controlling the chemical composition of seawater.

GEOSECS changed the way chemical oceanographers study the ocean by enabling them to use the techniques of other disciplines. It also radically altered the views of other scientists toward major ocean processes. Determining the rapid mixing and cycling of some ocean waters added much to our knowledge of how pollutants and other materials are distributed in the oceans. And it underscored the importance of the interaction between the ocean and atmosphere in this process. The exchange of gases (especially carbon dioxide) between the ocean and atmosphere is of special concern. Increased amounts of carbon dioxide are being introduced into the atmosphere from industrial activity; what impact this has on the ocean is a subject for future study. GEOSECS data will continue to be analyzed during the 1980s.

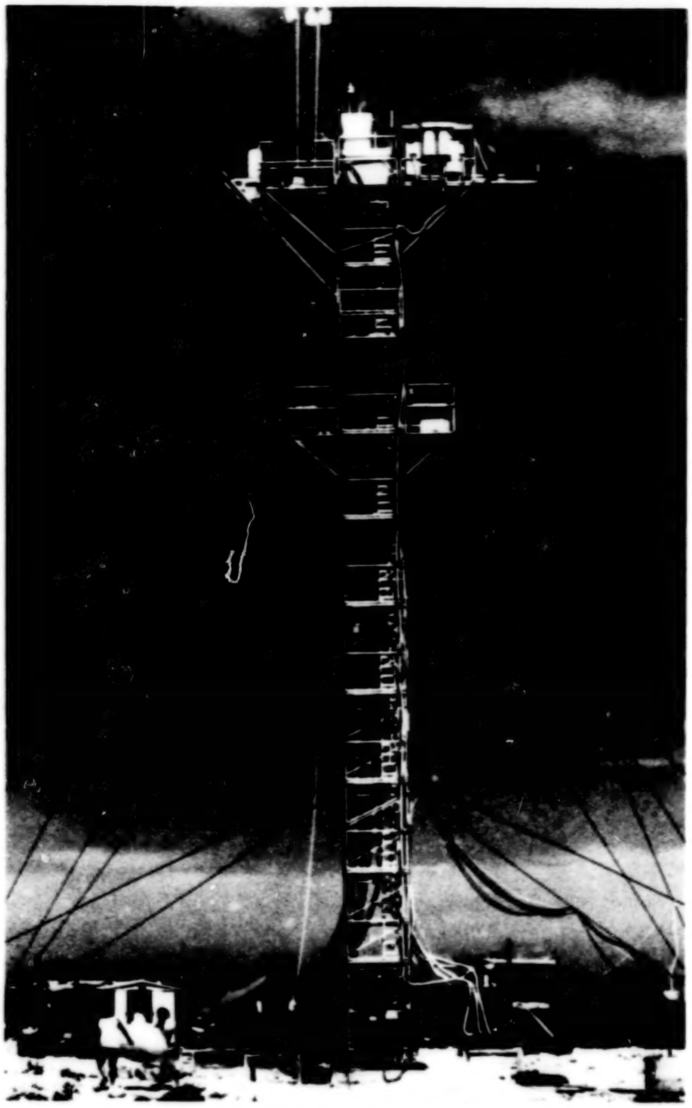
Sea-Air Exchange Project (SEAREX)

SEAREX scientists studied the little-understood exchange processes that control fluctuations of organic and inorganic compounds, both natural and pollutant, across the sea-air boundary. Eight American groups plus French and English teams of investigators collaborated in a tightly coordinated field and laboratory effort. The field programs studied several natural and pollutant materials, both organic and inorganic, in rain and in the atmosphere. Major SEAREX objectives have been to measure the atmospheric concentrations of certain heavy metals, radioisotopes, and trace organic compounds; to determine their exchange with the ocean surface; and to find the sources of these substances in the marine atmosphere.

A major SEAREX approach to determine atmospheric concentrations and fluxes on a global scale was sampling the atmosphere at sites far from major land masses and symmetrically located in the Northern and Southern Hemispheres. Both the relative land areas and the extent of emissions caused by human activities are markedly different in the two hemispheres, enhancing the contrast between land- and marine-derived materials. Heavily instrumented 18-meter towers were built in the Northern Hemisphere on the windward side of Bokandretok, a small uninhabited island near Enewetak Atoll, Marshall Islands, and in the Southern Hemisphere on Tutuila Island, American Samoa. Sampling periods covered eight consecutive weeks during both the wet and the dry seasons at these two locations.

A test experiment in 1978 at Pigeon Key, Florida, calibrated sampling and meteorological equipment, checked the logistics for the larger field effort, and detected potential contamination problems between the many groups involved. The Bokandretok experiment took place in March-April and July-August 1979 and the American Samoa field program in January-February and July-August 1981.

The first SEAREX field program at Enewetak provided samples of atmospheric particulate material and gases from the local trade winds. Analysis of these samples showed that certain potential pollutants, such as mercury and some organic



SEAREX instruments on this 18-meter tower collected atmospheric particulate material and gases from the northeast trade winds for eight weeks during the wet and dry seasons at Enewetak Atoll. Vans located near the base housed laboratories for sample analysis.

compounds, move primarily as gases and are removed from the air by interactions with particles.

An unexpected discovery was the very high content of alumina and terrestrial organic compounds in the particulate samples. Researchers believe this material came from the Asian deserts. This dust is carried at 3,000 meters above sea level (above the easterly trade winds) and into the Central Pacific, where it falls. The two eight-week experiments were of sufficient length to let SEAREX investigators measure the different rates at which this dust falls onto the sea. The proportion of alumina, some organic compounds, and certain continental radionuclides to marine-derived sodium in the atmosphere all decreased with time throughout the experiment. These results were consistent with the meteorological studies predicting that dust input should be strongest in March and then subside through August.

This was the first direct indication that Asian dust can be carried into the equatorial Central Pacific. Later field experiments sampled airborne materials in the trade winds south of the equator at American Samoa. These and other studies will expand our knowledge about atmospheric transport of dust and pollutants from the land to remote ocean locations on a global scale.

In other field sampling work, SEAREX investigators looked at ways in which materials move in the opposite direction—from the ocean to the atmosphere. University of Rhode Island researchers developed the Bubbling Interfacial Microlayer Sampler, a device mounted on a small boat and designed to sample the very thin surface layer of the ocean, which acts as an important source of particulate material entering the atmosphere. Two field programs used the sampler. The first took place in August 1979 in the northwest Atlantic (Sargasso Sea) and the second in March 1981 in the southeast Pacific. The two cruises were in contrasting areas, the Sargasso Sea being rather barren and the coast of Peru a very active upwelling zone of high productivity.

Because of the very low levels of organic compounds in the materials studied, SEAREX analyses used the most sensitive and sophisticated organic analytical techniques yet available, notably computerized glass capillary gas chromatography and mass spectrometry. Similarly, the trace metal concentrations are very low, requiring equally sophisticated instrumentation, including neutron-activation analysis. Studies of the data from this program and the new investigations it generated will carry on into the 1980s.

Pollutant Responses In Marine Animals (PRIMA)

The PRIMA project developed and evaluated indexes of subtle damage in marine animals exposed to low levels of common toxic chemical pollutants. Results of this work will provide early warnings of pollutant-induced stress so that actions can be taken before there is extensive—perhaps irreversible—damage to either organisms or ecosystems.

Several species of fish, clams, crabs, and worms were chosen for study because of their important roles in marine ecosystems and their availability and suitability for experimentation. The species studied represent very different types of animals, and the degree and similarity of their responses show how useful the indexes are in predicting the responses of other animals exposed to pollution. Six principal investigators at five different institutions conducted the PRIMA research. Their experimentation and sampling procedures have been closely coordinated to ensure that the projects are comparable.

PRIMA concentrated on widespread representatives of organic pollutants, including polycyclic aromatic hydrocarbons (such as benzo-[a]-pyrene, a combustion product), chlorinated aromatic hydrocarbons (hexachlorobenzene, a fungicide), and chlorinated phenols (pentachlorophenol, a general biocide used as a preservative). These compounds were chosen because large amounts of them come into the environment; they tend to enter, and persist in, the ocean; and they accumulate in and are toxic to animals. They concentrate in fat tissues, such as cell membranes and other fat deposits of animals. Marine organisms thus serve as sinks for these compounds, which can accumulate in an animal at levels thousands of times higher than the levels present in

BEST DOCUMENT AVAILABLE

Marine animal tissue samples are being prepared in a Texas A & M University laboratory for analysis of organic pollutants. The samples are homogenized and extracted with various organic solvents; the extracts are then purified. Final quantities are determined by high-pressure liquid chromatography or gas chromatography.

the water. These pollutants can have toxic effects on the animals and affect their ability to reproduce. They can also be transported by fish to other parts of the environment, or even transferred to humans when an affected animal is eaten.

The features examined in the representative animals included cell and tissue structure, biochemistry of blood and other tissues, immunization mechanisms, and other stress indicators. Reproductive indexes were also examined. Changes in these features were linked to pollutant levels in the animal and to the animal's ability to transform a pollutant into another chemical structure.

In fish, this biological transformation takes place principally in the liver, but the enzymes responsible are in other organs, such as gills, kidney, testis, ovary, and heart. This process of biotransformation by enzymes produces water-soluble products that can be eliminated easily from the body. In many cases this metabolism and excretion would reduce the toxic effect of the pollutant. However, in some pollutants the change actually increases their capacity to cause damage. The products of biotransformation may interact with critical cell molecules, such as DNA or protein, and can lead to cell death or disease.

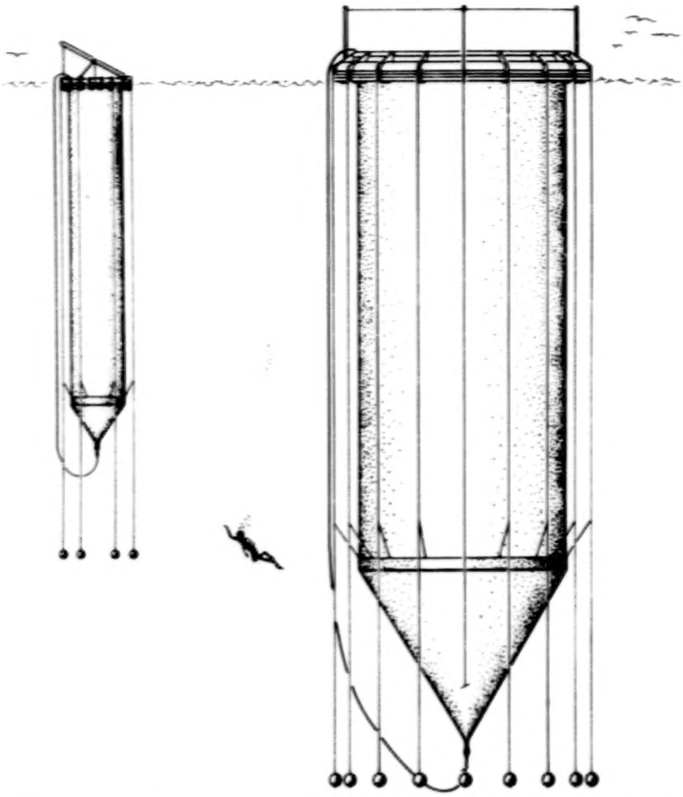
Enzymes such as those that metabolize pollutants also help form and activate many important molecules in an animal. Thus they are important in maintaining the correct balance of substances, such as steroid hormones, which control reproduction and other bodily functions. The study of steroid effects and their interaction with pollutants shows how the latter act and how complex systems regulate physiological processes.

PRIMA researchers developed new ways to handle pollutants experimentally and to measure low pollutant concentrations in water, sediments, and tissues. With these techniques, rates and amounts of accumulation and elimination were measured for pollutants in fish. PRIMA scientists also examined characteristics of the various systems in unstressed animals; they then established how well these animals could resist effects of the various pollutants. Comparable studies of these organisms in the field followed. The findings show that pollutant exposure can affect reproductive processes, susceptibility to disease, and biotransformation capability.

Controlled Ecosystem Pollution Experiment (CEPEX)

CEPEX investigators pioneered the use of large enclosed volumes of seawater to experiment with natural populations exposed to low levels of pollutants. CEPEX had three objectives: (1) to determine the effects of various pollutants on

Injection of a prepared sample into a high-pressure liquid chromatograph is the last step in PRIMA analysis that can detect a billionth of a gram of pollutant in animal tissue.

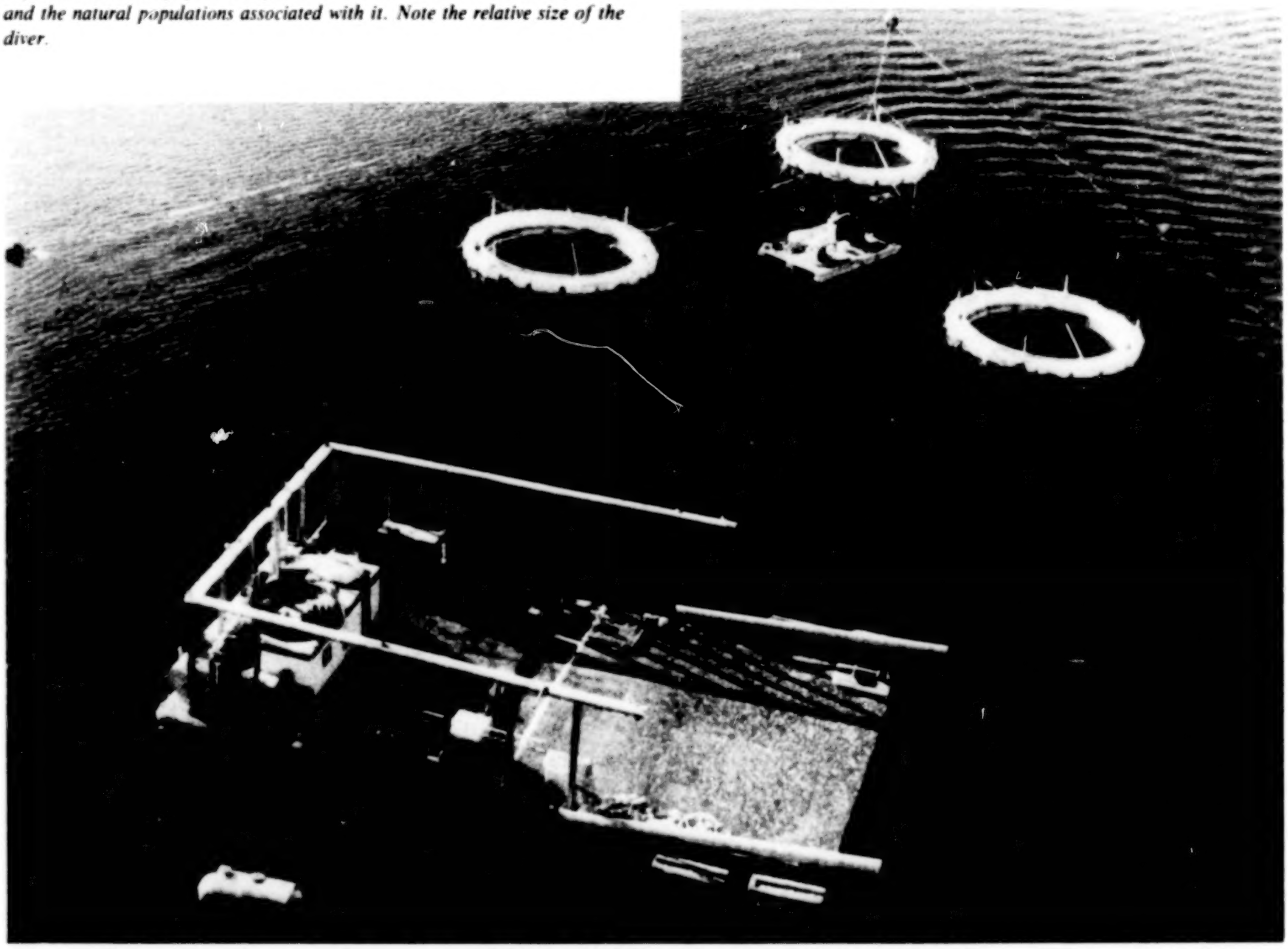


The CEPEX *project first used the enclosure of a natural population for pollution experiments. Its large plastic bags contained 68 to 1,700 cubic meters of water and the natural populations associated with it. Note the relative size of the diver.*

bacteria and on phytoplankton and zooplankton (communities of microscopic, free-floating plants and animals) in a large experimental ecosystem; (2) to evaluate changes in the uptake of nutrients under different levels of pollutant stress; and (3) to identify chemical variations in experimental ecosystems subjected to pollution over periods of 60 to 90 days. The effort involved scientists from nine American institutions, as well as Canadian and British laboratories.

CEPEX investigators developed and tested different sizes of large, double-layered plastic bags, or controlled experimental ecosystems (CEEs). The bags were suspended and filled with water containing natural populations of plants and animals from Saanich Inlet, offshore from the Institute of Ocean Sciences in Sydney, British Columbia, Canada (one of the participating institutions in CEPEX). The CEEs contained from 68 to 1,700 cubic meters of water, comparable to the volume of a modest-sized room to a modest two-story house. In most experiments, three bags were involved simultaneously to provide replicates for statistical purposes. They were open to the atmosphere and organic debris accumulated at the bottom of each.

The basic CEPEX plan was to measure changes in temperature, salinity, nutrient concentration, zooplankton, and phytoplankton in the trapped Saanich Inlet water, and the



The controlled experimental ecosystem bags were suspended in Saanich Inlet, offshore from the Institute of Ocean Sciences in Sydney, British Columbia.

organisms in it, for up to 60 days. Measured amounts of different pollutants were added to two of the bags, and daily or weekly changes in the parameters were compared to those observed in the third, untouched control bag.

CEPEX planners stressed that small-scale laboratory experiments to determine the effects of pollution on marine species had resulted in unrealistic results, primarily because complex relationships known to exist in marine ecosystems could not be simulated in beakers or bottles. The large-scale CEEs were intended to reduce this disparity and produce more realistic results from systems that more closely approximated the natural marine environment.

Bacteria and phytoplankton in large plastic bags were found to respond much as they do in conventional laboratory glassware, but zooplankton reacted to pollutants in lower concentrations in the CEEs than in laboratory tests. The CEPEX results indicate that susceptibility of organisms to toxic compounds is a function of size. For example, adults are less sensitive than juveniles, and large organisms are less sensitive than small ones. Within populations of organisms, generation time is a prime factor in determining recovery. Thus bacteria, with their rapid reproduction rates and large numbers of species, show rapid recovery with pollution-resistant strains. Zooplankton recover more slowly, and phytoplankton recover at intermediate rates.

The same sequence of events or response comes from exposure of the ecosystem to different pollutants. For example, marine ecosystems respond in the same way to fluctuations of natural factors, such as nutrient turbulence or light, as they do when subjected to unnatural concentrations of most man-made pollutants. The CEPEX results reveal that the ocean has a remarkable capacity to recover from localized disturbances.

One of the most significant contributions of this project was to document how community structure, or the relative abundance of organisms, changes in response to pollutant stress. The proportion in numbers of one group of organisms (e.g., diatoms) to another (e.g., zooplankton) remains fairly constant in unstressed or nonpolluted environments. As pollution or other stress increases, this proportion changes in relation to the severity of the stress. Knowing this proportion, researchers can accurately assess the health and relative level of pollution of a marine environment.

A diver tends one of the CEPEX plastic enclosures.

CEPEX was a pioneering effort to experiment with controlled ocean volumes. It showed much about the effects of pollutants on simple marine ecosystems. But there is much to learn about the use of large enclosures for such studies.

After CEPEX ended in 1980, the Canadian participants continued the Saanich Inlet facility and are actively pursuing the same experimental approaches with scientists from Japan and West Germany. Developing methods to enclose and study large volumes of seawater and their natural populations may well be one of the major contributions of CEPEX to the ocean sciences.

Epilog

One measure of the International Decade's success is how well the various projects met IDOE goals. In brief, these goals were to:

- Preserve the ocean environment and improve environmental forecasting.
- Assess the mineral potential of the deep-ocean floor.
- Develop an ocean monitoring system.
- Improve worldwide ocean-data exchanges.
- Help plan ocean exploration and assure better use of capabilities.

A principal finding of IDOE projects is that the open ocean waters are relatively free of pollution; most of these problems are confined to coastal ocean waters and estuaries.

During the Decade, oceanography became less and less descriptive and increasingly quantitative. New instruments had to be developed and sample handling procedures established to ensure quality data that would meet the sensitivity and accuracy requirements of scientists and regulatory agencies.

The IDOE involved no studies of ocean waste disposal. In 1972, the Ocean Dumping Act (P.L. 92-532) and the Water Quality Act (P.L. 92-500) assigned this type of research to the Environmental Protection Agency and the National Oceanic and Atmospheric Administration (NOAA).

One of the most dramatic results of the Decade was learning how to predict the interruption of upwelling off Peru (El Niño) six to nine months before it happens. The discovery that El Niños on the Peruvian coast are caused by changes in the winds along the equator permits valuable forecasts. These may help prevent a recurrence of the disastrous effects the 1972 El Niño had on the Peruvian fishery (combined with overfishing), as well as worldwide upsets in the abundance and price of protein.

Forecasting seasonal climate several months ahead still remains in the developmental stages. Some scientists are confident that useful prediction techniques can be developed; many others remain unconvinced. Work begun by IDOE's North Pacific Experiment (NORPAX) is still under way with support from NOAA and other U.S. government agencies.

IDOE scientists compiled available data on the distribution and composition of manganese nodules in the oceans. Their maps of the distribution and abundance of valuable metal (copper, nickel, cobalt) guided later work by private companies and government agencies through the last half of the 1970s.

IDOE-supported exploration off the mid-ocean ridge crests showed widespread and massive metal sulfide deposits of potential commercial value. These discoveries (along with the hydrothermal vents) came too late in the Decade for extensive study under IDOE projects. However, further exploration of these deposits is virtually certain because of their importance in understanding the chemistry of the oceans.

No ocean monitoring system was developed during the Decade, owing in part to lack of funding.

Archiving and exchange of data were major activities. In the United States, IDOE data exchange and dissemination were handled by NOAA's Environmental Data and Information Service, with support from the National Science Foundation. During the Decade, the National Oceanographic Data Center was expanded, and it will continue to handle scientific data from IDOE and other oceanography projects as part of its basic mission.

IDOE changed the way oceanographers study the ocean. No longer does it suffice to describe singular unrelated events. IDOE projects showed that ocean events are interrelated and that cooperative, large-scale, multidisciplinary projects are required to understand many ocean problems fully. Planning for support of such projects continues at the National Science Foundation since the termination of the IDOE.

Appendix 1:
Universities and Institutions Participating in the IDOE

Alabama, University of
Alaska, University of
American National Standards Institute
Arizona, University of

Battelle Memorial Institute (Columbus, OH)
Bermuda Biological Station
Brookhaven National Laboratory (Upton, NY)
Brown University

California Institute of Technology
California Technological Institute
California-Berkeley, University of
California-Los Angeles, University of
California-San Diego, University of
California-Santa Barbara, University of
Case Western Reserve University
City University of New York, City College
City University of New York, Queens College
Columbia University, Lamont-Doherty
  Geological Observatory
Connecticut, University of
Cornell University

Delaware, University of
Duke University

Florida State University
Florida, University of

Georgetown University

Harvard University
Hawaii, University of, Institute of Geophysics

Indiana, University of
Institute of Ecology
Inter-American Tropical Tuna Commission

Jet Propulsion Laboratory (Pasadena, CA)
Johns Hopkins University

Louisiana State University

Maine, University of
Massachusetts Institute of Technology
Miami, University of
Michigan State University
Michigan, University of

National Academy of Engineering
National Academy of Sciences
National Center for Atmospheric Research
New York University
Northeast Research Foundation, Bigelow Laboratory
Nova University

Oregon State University

Puerto Rico, University of
Princeton University

Rhode Island, University of
Rice University

San Diego State University
San Francisco State University
San Jose State University
Seattle Pacific College
Skidaway Institute of Oceanography
Sloane Kettering Institute
South Carolina, University of
Southern California, University of
Stanford University
State University of New York-Albany
State University of New York-Buffalo

Texas A&M University
Texas-Austin, University of
Texas-Galveston, University of

Virginia, University of

Washington, University of
Washington State University
Woods Hole Oceanographic Institution
Wisconsin, University of

Yale University

Major U.S. Projects in International Decade of Ocean Exploration

Programs and Projects	Number of Institutions	Number of Scientific Investigators	Year Initiated	Expected Year of Completion	Estimated Total (in Millions of Dollars)	Other U.S. Agencies Providing Funds
Environmental Forecasting						
NORPAX	28	45	1971	1982	$29.7	ONR[1]
CLIMAP	8	22	1971	1980	8.0	
MODE	16	45	1971	1974	8.0	ONR, NOAA[2]
ISOS	9	16	1974	1981	10.2	
POLYMODE	12	35	1975	1982	15.5	ONR, NOAA
Environmental Quality						
GEOSECS	14	28	1971	1980	23.5	ERDA[3]
Pollutant Baseline	17	30	1971	1978	2.3	
Pollutant Transfer	9	10	1972	1979	10.0	
Biological Effects						
Field (CEPEX)	5	10	1973	1980	10.5	
Laboratory	6	8	1973	1979	10.0	
SEAREX	9	15	1977	1983	4.6	
PRIMA	5	6	1978	1984	2.4	
Seabed Assessment						
South Atlantic Margins	2	15	1971	1975	4.0	
Nazca Plate	3	25	1971	1977	6.0	
FAMOUS	4	10	1972	1975	2.0	ONR/NOAA
Manganese Nodules	10	18	1972	1977	4.0	
MANOP	11	21	1977	1984	8.0	
Galapagos	3	9	1976	1979	1.4	
Rise	5	7	1977	1980	1.3	
SEATAR	7	15	1975	1980	5.4	
CENOP	11	15	1978	1982	2.8	
Living Resources						
CUEA	13	11	1972	1979	15.2	
SES	10	11	1974	1981	7.0	

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[1] Office of Naval Research

[2] National Oceanic and Atmospheric Administration

[3] Energy Research and Development Administration